The Development of a SmartAbility Framework to Enhance Multimodal Interaction for People with Reduced Physical Ability

by

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Acronyms / Abbreviations

ACSII	American Standard Code for Information Interchange
ADB	Android Debug Bridge
AND	'AND' binary logical operator
ALS	Amyotrophic Lateral Sclerosis
ATRS	Automated Transport and Retrieval System
AVI	Audio Video Interleave
CMM	Capability Maturity Model
Cont.	Continued
CP	Cerebral Palsy
DLL	Dynamic Linked Library
Dr.	Doctor
DSHS	(The Washington State) Department of Social and Health Services
ECoG	Electrocorticography
EEG	Electroencephalogram
EIDD	European Institute for Design and Disability
FR	Functional Requirement
FTP	File Transfer Protocol
GmbH	Gesellschaft mit beschränkter Haftung (German business/company)
GPS	Global Positioning System
GUI	Graphical User Interface
HCI	Human Computer Interaction
HMD	Head Mounted Display
HoQ	House of Quality
HSI	Human System Integration
HTA	Hierarchical Task Analysis

HTML	Hyper Text Mark-up Language
ICF	International Classification Framework
ICF-CY	International Classification Framework – Children and Youths
ICIDH	International Classification of Impairment, Disability and Handicap
Inc.	Incorporated (American business/company)
INCOSE	International Council on Systems Engineering
iOS	iPhone Operating System
IR	Interoperability Requirement
ISO	International Organisation for Standardization
JPEG	Joint Photographic Experts Group
Ltd.	Limited (British business/company)
LiDAR	Light Detection and Ranging
MD	Muscular Dystrophy
MHADIE	Measurement of Health and Disability in Europe
MND	Motor Neuron Disease
MoSCoW	Must have, Should have, Could have, and Won't have but would like (Requirements)
MR	Maintainability Requirement
MS	Multiple Sclerosis
NASA	National Aeronautics and Space Administration
NCMRR	National Center for Medical Rehabilitation Research
NIST	National Institute of Standards and Technology
OA	Osteoarthritis

OI	Osteogenesis Imperfecta
OpenURI	Open Uniform Resource Identifier (Recon Jet application)
PBP	Progressive Bulbar Palsy
PLS	Primary Lateral Sclerosis
PMA	Progressive Muscular Atrophy
PNG	Portable Network Graphic
Powerchair	Powered Wheelchair
PR	Performance Requirement
Prof.	Professor
PTR	Portability Requirement
QFD	Quality Function Deployment
QUIS	Questionnaire for User Interaction Satisfaction
RASoS	Risk Assessment for Systems of Systems (Framework)
ReconOS	Recon Operating System
RFID	Radio-frequency Identification
ROM	Range of Movement
RR	Reliability Requirement
SB	Spina Bifida
SCI	Spinal Cord Injury
SDK	Software Development Kit
SEBoK	Systems Engineering Body of Knowledge
SEI	Software Engineering Institute
SFR	Safety Requirement
SoI	System of Interest
SoS	System of Systems
SoSE	System of Systems Engineering
s.r.o.	společnost s ručením omezeným (Czech

	business/company)
SUS	System Usability Scale
SWORD	Subjective Workload Dominance
T-AREA-SoS	Trans-Atlantic Research and Education Agenda in System of Systems
TLD	Tracking-Learning-Detection
TLX	Task Load Index
UK	United Kingdom
UsabilityBoK	Usability Body of Knowledge
UR	Usability Requirement
URL	Uniform Resource Locator
USA	United States of America
USB	Universal Serial Bus
WAV	Wheelchair Accessible Vehicle
WHO	World Health Organisation
Wi-Fi	Wireless Fidelity
WPA2	Wi–Fi Protected Access II
XML	Extensible Mark-up Language

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Abstract

Assistive technologies are an evolving market due to the number of people worldwide who have conditions resulting in reduced physical ability (also known as disability). Various classification schemes exist to categorise disabilities, as well as government legislations to ensure equal opportunities within the community. However, there is a notable absence of a process to map physical conditions to technologies in order to improve Quality of Life for this user group.

This research is characterised primarily under the Human Computer Interaction (HCI) domain, although aspects of Systems of Systems (SoS) and Assistive Technologies have been applied. The thesis focuses on examples of multimodal interactions leading to the development of a SmartAbility Framework that aims to assist people with reduced physical ability by utilising their abilities to suggest interaction mediums and technologies. The framework was developed through a predominantly Interpretivism methodology approach consisting of a variety of research methods including state-of-the-art literature reviews, requirements elicitation, feasibility trials and controlled usability evaluations to compare multimodal interactions. The developed framework was subsequently validated through the involvement of the intended user community and domain experts and supported by a concept demonstrator incorporating the SmartATRS case study.

The aim and objectives of this research were achieved through the following key outputs and findings:

- A comprehensive state-of-the-art literature review focussing on physical conditions and their classifications, HCI concepts relevant to multimodal interaction (Ergonomics of human-

system interaction, Design For All and Universal Design), SoS definition and analysis techniques involving System of Interest (SoI), and currently-available products with potential uses as assistive technologies.

- A two-phased requirements elicitation process applying surveys and semi-structured interviews to elicit the daily challenges for people with reduced physical ability, their interests in technology and the requirements for assistive technologies obtained through collaboration with a manufacturer.
- Findings from feasibility trials involving monitoring brain activity using an electroencephalograph (EEG), tracking facial features through Tracking Learning Detection (TLD), applying iOS Switch Control to track head movements and investigating smartglasses.
- Results of controlled usability evaluations comparing multimodal interactions with the technologies deemed to be feasible from the trials. The user community of people with reduced physical ability were involved during the process to maximise the usefulness of the data obtained.
- An initial SmartDisability Framework developed from the results and observations ascertained through requirements elicitation, feasibility trials and controlled usability evaluations, which was validated through an approach of semi-structured interviews and a focus group.
- An enhanced SmartAbility Framework to address the SmartDisability validation feedback by reducing the number of elements, using simplified and positive terminology and

incorporating concepts from Quality Function Deployment (QFD).

- A final consolidated version of the SmartAbility Framework that has been validated through semi-structured interviews with additional domain experts and addressed all key suggestions.

The results demonstrated that it is possible to map technologies to people with physical conditions by considering the abilities that they can perform independently without external support and the exertion of significant physical effort. This led to a realisation that the term 'disability' has a negative connotation that can be avoided through the use of the phrase 'reduced physical ability'. It is important to promote this rationale to the wider community, through exploitation of the framework. This requires a SmartAbility smartphone application to be developed that allows users to input their abilities in order for recommendations of interaction mediums and technologies to be provided.

This Doctorate research has been disseminated through a number of peer-reviewed publications at international conferences and in journals.

Author's Declaration

Some of the material contained within this thesis has been previously published in the conference and journal papers referenced in section 1.6.

Keywords

Assistive Technologies, Accessibility, Disability, Framework, Human Computer Interaction, Multimodality, System of Systems

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Chapter 1 Introduction

This chapter describes the research rationale by providing the background, problem overview, aim, objectives and contributions to knowledge.

1.1 Research Background

There is an ever-increasing market for assistive technologies (Gallagher and Petrie 2013), as approximately 500 million people worldwide have a disability (referred to as 'reduced physical ability' in this research) that affects their interaction with society and the environment (Cofré et al. 2012). It is therefore important to encourage independent living and improve the Quality of Life for people with reduced physical ability.

The research only focuses on reduced physical ability, as reduced cognitive abilities are considered outside the scope of a framework that recommends technologies based on the actions that users can perform independently. It is recognised that physical abilities can vary in severity and it will be important for a framework to cater for these differences.

A number of reduced physical abilities exist as human beings are susceptible to diminishing health and potential development of reduced physical ability at any point in life (Kostanjsek 2011). Reduced physical abilities can either be viewed as congenital (i.e. from birth) or acquired (e.g. due to a traumatic event). Frameworks have been developed since the 1950s to classify reduced physical ability into generic types, with the current classification being the International Classification of Functioning Disability and Health (ICF) Framework developed by the World Health Organisation (WHO). According to the UK Equality Act 2010 (in regards to disability), a physical impairment can have a substantial and long-term negative affect on an individual's ability to perform normal activities. The purpose of the Act is to protect people with reduced physical ability by ensuring equal opportunities and improve Quality of Life in social settings such as public buildings, transportation and educational institutions (Government Equalities Office 2010). In developing countries, there are lower standards of equality for reduced physical ability (World Health Organization 2011) and therefore greater challenges are posed, even in social settings. However, the Equality Act does not apply to the home environment and general daily activities. Within the home environment there is no such protection; Quality of Life can be improved with the use of living aids such as automated doors, electric beds, stairlifts and hoists. The author's personal experience has increased awareness that in addition to living aids, the development of assistive technologies has the potential to further enhance independence. However, it has been shown that people with reduced physical abilities are not always aware of the enhancements in technology that could improve their Quality of Life and reduce reliance on others including family and support workers (Ari and Inan 2010). This implies that there is a significant absence of contribution to relate reduced physical abilities to technologies, which could be fulfilled by the development of a framework linking the two domains.

1.2 Key Terminology

It is important for this thesis to define a common language and therefore the following is a list of recurring terminologies that are discussed further in chapter two.

- **People with reduced physical ability:** this term is also known as disability, which is “a condition or function judged to be significantly impaired relative to the usual standard of an individual or group…used to refer to individual functioning including physical impairment, sensory impairment, cognitive impairment, intellectual impairment, mental illness and various types of chronic disease” (Disability World 2016a). However, to promote a positive attitude within the research, ‘reduced physical ability’ will be used.

- **Range of Movement (ROM):** also known as Range of Motion and refers to “the movement about the axis of a joint”. (Kielhofner 2006).

- **Quality of Life:** “the opportunities that are available to people from which choices and decisions can be made” (Ontario Adult Autism 2016). Quality of Life can be viewed as Physical Being (i.e. body and health), Psychological Being (i.e. thoughts and feelings), Practical Becoming (i.e. daily activities) and Leisure Becoming (i.e. fun and enjoyment).

- **System:** a "construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance" (Rechtin 2000).

- **System of Systems (SoS):** an "integration of a finite number of constituent systems which are independent and operatable, and which are networked together for a period of time to achieve a certain higher goal" (Jamshidi 2009; SEBoK 2016b).

- **Multimodality:** a characteristic of systems "that process two or more 7combined user input modes in a coordinated manner with multimedia outputs" (Oviatt 2003).

- **Assistive Technology:** "any product or service designed to enable independence for disabled and older people" (Williams-Zahir 2015).

- **Powerchair:** also known as a motorised wheelchair, electric wheelchair or electric powered wheelchair and is "a wheelchair that is propelled by means of an electric motor rather than manual power" (Disability World 2016b).

- **Automated Transport and Retrieval System (ATRS):** a technically-advanced system developed by Freedom Sciences Inc. in 2008 to provide "a reliable, robust means for autonomously docking a wheelchair onto a lift platform to eliminate the need for an attendant…accomplished through LIDAR-based localization" (Gao et al. 2008).

- **SmartATRS:** a smartphone system that is "one constituent system within a pervasive System of Systems that supports the interaction between a powerchair and a vehicle" (Whittington and Dogan 2016) and operates ATRS by replacing the small wireless keyfobs.

- **Framework:** "a written or visual presentation that explains either graphically, or in narrative form, the main things to be studied – the key factors, concepts or variables - and the presumed relationship among them" (Miles and Huberman 1994).

1.3 Problem Overview and Stakeholders

As the author has reduced physical ability, the reliance on others for transportation was an initial incentive to investigate solutions available for independent driving. A potential solution is a Wheelchair Accessible Vehicle (WAV), but this has the distinct disadvantage of requiring permanent vehicle modifications, including the removal of rear crumple zones, to allow installation of a ramp, thus presenting a significant safety risk to the occupants. The author uses the Automated Transport and Retrieval System (ATRS) (Gao et al. 2008), a technically-advanced system developed by Freedom Sciences Inc. and featured in the New Scientist magazine (Kleiner 2008). The system incorporates robotics technology and Light Detection and Ranging (LiDAR) to autonomously dock a powered wheelchair (powerchair) onto a platform lift fitted in the rear of a vehicle whilst a disabled driver is seated in the driver's seat (illustrated in Figure 1). ATRS can be installed into a standard Multi-Purpose Vehicle (MPV) without the removal of any crumple zones, thus maintaining the occupants' protection. ATRS is further described in section 2.8.2. The installation of ATRS enables independent driving, however, the operation of small wireless keyfobs to control the ATRS components, is perceived to be a significant limitation.

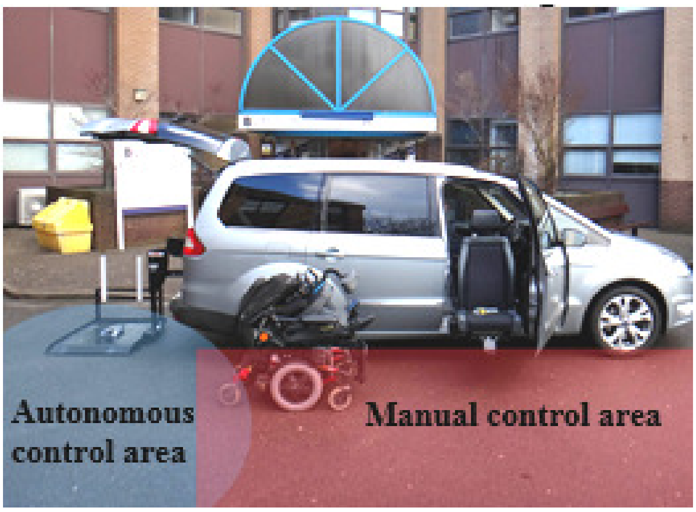

Figure 1: Autonomous docking of a powerchair using ATRS

This constraint led to the author investigating the replacement of keyfobs with a smartphone system (SmartATRS) with consideration given to enhancing safety and user feedback. As SmartATRS relied on the integration of constituent systems (i.e. ATRS, relay board, wireless router and a smartphone) that interoperate, it was therefore considered as a System of Systems (SoS) and a basis for conducting Human Computer Interaction (HCI) research to enhance multimodal interaction for people with reduced physical ability.

Through the involvement of the user community and an industrial partner, the beneficiaries of the research were established. The main user community of people with reduced physical ability was obtained through collaborations with the Liveability charity who manage the Victoria Education Centre special educational needs school (Livability 2016a) and Talbot Manor residential home (Livability 2016b) in Poole. Victoria Education Centre specialises in education, therapy and care for students between the ages of 3 and 19, as well as a residential transition service for students aged 18-25. Due to the complexity surrounding parental/carer consent ethics for people under 16 years of age (Barnard et al. 2012), only the students over the age of 16 were involved in the research. Talbot Manor provides care and support for people with reduced physical ability in a home environment with individual rooms and communal spaces including a garden. The 2016 Mobility Roadshow at Silverstone (Mobility Choice 2016) provided an additional user base to conduct usability evaluations and framework validations. The roadshow is organised by the Mobility Choice charity and is the United Kingdom (UK) consumer event for disability where assistive technology and other disability manufacturers exhibit their products.

An industrial collaboration was formed with Dynamic Controls who are the global manufacturers of controls for powered wheelchairs, including the iPortal product that was integrated into the SmartATRS case study. The head office of Dynamic Controls is in Christchurch (New Zealand), although there are offices in the UK, United States of America (USA) and Asia. The company provided input to the manufacturer requirements and elicitation phase through utilisation of their knowledge of the assistive technology domain.

1.4 Aim, Objectives and Scope

The aim of the research is:

To develop a framework to enhance multimodal interaction for people with reduced physical ability.

The aim is addressed through the following objectives:

1. **To investigate the state-of-the-art focusing on reduced physical ability, Human Computer Interaction (HCI) and System of Systems (SoS) that contribute to the assistive technology domain.**

   It is necessary to consider reduced physical ability in terms of: disability classification, impairments and Range of Movement (ROM). Multimodal Interactions, Ergonomics of human-system interaction and assistive technologies are viewed as being related aspects of HCI. The characterisation, definition and description of SoS, as well as the application of System of Interest (SoI) are important areas of SoS to investigate. To contribute to the assistive technology domain, it is essential to understand processes regarding industrial developments.

2. **To elicit user and manufacturer requirements for a concept demonstrator, in terms of interaction mediums and technologies.**

Due to a limited user community of available powerchair users, the interaction mediums and technology requirements need to be elicited using a mixed-method approach of surveys and semi-structured interviews to maximise the response rate. As the manufacturer is based in New Zealand, requirements need to be elicited through electronic methods (i.e. email and Skype).

3. **To conduct feasibility trials and controlled usability evaluations of assistive technologies involving the user community.**

   In order to conduct initial assessments of technology before inclusion into a framework, it is crucial to perform feasibility trials. Such trials can be performed without the involvement of the user community to determine whether controlled usability evaluations should be performed. To guide the evaluations, it is essential to involve the user community of people with reduced physical ability and therefore adopt the Ergonomics of human-systems interaction ISO standard (ISO 9241-210:2010), formally known as Human-centred Design. This indicates a Participative Enquiry research strategy where the evaluation results contribute to the design of a framework.

4. **To develop and validate a framework reflecting the mappings between disability type and technology.**

   A framework is to be developed, supported by a concept demonstrator illustrating the integration of technology to an existing assistive technology. A framework can be validated through the engagement of the user community and domain experts utilising approaches including focus groups and elaborated scenarios. Such validation methods are described further in chapter three.

5. **To disseminate a framework and set of recommendations for the assistive technology domain.**

   Recommendations for the exploitation of a framework will be provided to the assistive technology domain (manufacturers, charities and special educational needs schools) in terms of how the framework could be utilised. Secondly, recommendations will be disseminated regarding lessons learnt from the requirement elicitation phase, technology feasibility trials, controlled usability evaluations and framework development.

The scope of the research did not include developing new technologies, as 'off-the-shelf' technologies can only be incorporated into a framework. The domains of data analytics, sensor technology and the development of programming algorithms were outside the scope of the research, as the research concerns user interactions with existing technologies.

1.5 Contributions to Knowledge

Key Contribution

1. Establishing a novel framework to map and recommend interaction mediums and technologies based on the physical abilities of users *(Objective 4 – Framework Establishment).*

Supplementary Contributions

2. Determining technologies that have the potential to assist people with reduced physical ability and hence assessing their usability through controlled experimentations *(Objective 3 – Technology Trials and Evaluations).*

3. Identifying the preferences and understanding of currently-available technologies for people with reduced physical ability (*Objective 1 – State-of-the-art Review, Objective 2 – Requirements Elicitation)*.

Potential Future Impact Contributions

4. Informing computing and healthcare domain experts of the potential framework usefulness for the design of assistive technologies and ongoing medical support and rehabilitation *(Objective 5 – Framework Dissemination)*.

5. Advising people with reduced physical abilities of the capability of the framework to recommend suitable technologies *(Objective 5 – Framework Dissemination)*.

6. Highlighting that 'reduced physical ability' has a positive connotation over 'disability', as it focuses on the actions that

users can perform rather than cannot perform *(Objective 5 – Framework Dissemination)*.

1.6 Publications

This research has been disseminated through the following conference and journal papers:

Whittington, P., Dogan, H. and Phalp, K., 2015a. Evaluating the Usability of an Automated Transport and Retrieval System. The 5th International Conference on Pervasive and Embedded Computing and Communication Systems, Angers, France, 11-13 February 2015. 59-66. Science and Technology Press, Lisbon, Portugal.

Whittington, P., Dogan, H. and Phalp, K., 2015b. SmartPowerchair: to boldly go where a powerchair has not gone before. Ergonomics & Human Factors 2015, Daventry, UK, 13-16 April 2015. 233-240. CRC Press, London, UK.

Whittington, P. and Dogan, H., 2015a. SmartPowerchair: A Pervasive System of Systems. The 10th International Conference on System of System Engineering, San Antonio, TX, USA, 18-20 May 2015. IEEE Press, New York, NY, USA.

Whittington, P. and Dogan, H., 2015b. Improving life for people with disabilities. The Ergonomist, 542, 12-13.

Whittington, P. and Dogan, H., 2016a. SmartDisability: A smart system of systems approach to disability. The 11th International Conference on System of System Engineering, Kongsberg 12-16 June 2016. New York, NY: IEEE Press. Available from:

http://ieeexplore.ieee.org/document/7542943/ [Accessed 7th October 2016].

Whittington, P. and Dogan, H., 2016b. Improving user interaction through a SmartDisability Framework. British HCI 2016 Conference, Bournemouth 11-15 July 2016.

Whittington, P. and Dogan, H., 2016c. A SmartDisability Framework: enhancing user interaction. British HCI 2016 Conference, Bournemouth 11-15 July 2016.

Whittington, P. and Dogan, H., 2017. SmartPowerchair: Characterisation and Usability of a Pervasive System of Systems. *IEEE Transactions on Human Machine Systems.* 47 (4), 500-510.

Ki-Aries, D., Dogan, H., Faily, S., Whittington, P. and Williams, C., 2017. From Requirements to Operation: Components for Risk Assessment in a Pervasive System of Systems. The 4th International Workshop on Evolving Security and Privacy Requirements Engineering, Lisbon, Portugal 4 September 2017.

1.7 Thesis Structure

The thesis is arranged into eleven chapters and a series of appendices as described below:

Chapter One: Introduction contains an introduction to the research including the background, key terminology, problem overview, aim, objectives and scope with contributions to knowledge. A summary of ATRS, as the case study for the research, is incorporated into the problem overview.

Chapter Two: Literature Review contains a comprehensive state-of-the-art review including reduced physical abilities and classifications, the Equality Act 2010, Range of Movement (ROM) as a determinant of ability and relevant Human Computer Interaction (HCI) concepts concerning the design of accessible systems. Further review is provided into applicable areas of multimodal interaction, System of Systems (SoS), assistive technologies and industrial development.

Chapter Three: Research Methodology discusses the principles behind the methodology including strategy and design. The research methods adopted are also described focussing on usability enquiry and evaluation, fictional personas, focus groups, Hierarchical Task Analysis, Cognitive Walkthrough, experimentations, simulations and validations.

Chapter Four: Research Results (i) Requirements Analysis describes the results from the requirements elicitation phase through surveys and semi-structured interviews involving user community and manufacturers. The phase determined the difficulties encountered in daily life and the current awareness of assistive technologies.

Chapter Five: Design of Architecture characterises the SmartPowerchair concept demonstrator as a SoS by the application of techniques including System of Interest (SoI). A description of the SmartATRS case study system architecture and an introduction to the RASoS initiative is also provided.

Chapter Six: Research Results (ii) Feasibility Trials presents results from initial feasibility studies to assess the suitability of assistive technologies for incorporation into the framework. The trialled technologies include electroencephalograph (EEG), Tracking Learning Detection (TLD), iOS Switch Control and smartglasses.

Chapter Seven: Research Results (iii) – Controlled Usability Evaluations contains the findings from the SmartATRS usability evaluations comparing keyfobs, touch, head and joystick based interactions. NASA TLX and SUS results are provided as indications of usability in terms of physical and mental demands, effort and frustration.

Chapter Eight: Research Results (iv) SmartDisability Framework 1.0 describes the first version of the framework prior to validation including the initial conceptual model containing the elements of Disabilities, Impairments, Range of Movement characteristics, Interaction Mediums, Technologies and Tasks.

Chapter Nine: Research Results (v) SmartAbility Framework 2.0 and 3.0 discusses the second version of the framework following initial validations at the Mobility Roadshow and a focus group of domain experts. The subsequent consolidation is also described based on final validations involving semi-structured interviews with domain experts.

Chapter Ten: Discussion presents the key contributions and findings from the research.

Chapter Eleven: Conclusions and Future Work describes the research conclusions, critically evaluates the research and outlines future research activities.

Appendices A to S present supporting materials associated with the research and are cross-referenced from the main body of the thesis.

1.8 Summary

The motivation for the research was supported by state-of-the-art literature reviews, stakeholder requirements, feasibility trials and controlled usability evaluations. This was also driven by the author's personal experience of having reduced physical ability and the desire to evaluate existing assistive technologies to potentially improve Quality of Life for users with similar physical conditions. The development of a framework addresses this motivation, as it would provide varying technology recommendations depending on the abilities of users.

Chapter 2 Literature Review

2.1 Introduction

Reduced physical ability, Human Computer Interaction, System of Systems and assistive technologies are the key areas related to the research. The current chapter expands on the key terminology defined in chapter one by presenting an in-depth state-of-the-art literature review into the relevant aspects to the research.

2.2 Reduced Physical Ability (Disability)

To avoid a negative connotation of the term 'disability' in the research, the phrase 'reduced physical ability' is adopted. However, literature commonly refers to disability being "a condition or function judged to be significantly impaired relative to the usual standard of an individual or group" (Disability World 2016a). There are varying forms of reduced physical ability that can either be congenital (i.e. from birth) or acquired (i.e. developed after birth), as further discussed in sections 2.2.2 and 2.2.3 respectively.

2.2.1 Classification Frameworks

Due to the diversity of conditions resulting in reduced physical ability, frameworks have been developed to characterise types. Example classification frameworks include; the model by Nagi in the 1950s to distribute welfare and economic aids (Nagi 2006), the Fundamental Principles of Disability conceptual model (Union of the Physically Impaired Against Segregation 1976), the International Classification of Impairment, Disability and Handicap (ICIDH) (World Health Organization 1980) and the National Center for Medical Rehabilitation Research of Bethesda's NCMRR model for rehabilitation by adapting the living environment (National Institute of Child Health & Human Development of the National Institutes of Health 1993).

The current international standard for classification (Cowan et al. 2012) is the International Classification of Functioning, Disability and Health Framework (ICF) (World Health Organization 2001a) that was a revision to the ICIDH, recognised in 191 countries (Masala and Petretto 2008). The development of the ICF was driven by the rationale that disability should not characterise individuals but be a complex interaction method between the person and the environment (Kostanjsek 2011). ICF was the predecessor with the aim of creating a standard language for defining and measuring health and disability. The framework considered health conditions and environmental factors that create disability. The development of the framework changed how disability is understood and measured (Kostanjsek 2011). The WHO subsequently produced the ICF-CY Framework for children and youths (World Health Organization 2007).

The functioning and disability framework components are diverse and describe body functions, structures and activities of people, participation in all areas of life and the environmental factors that affect these experiences. The interactions between the components are shown in Figure 2.

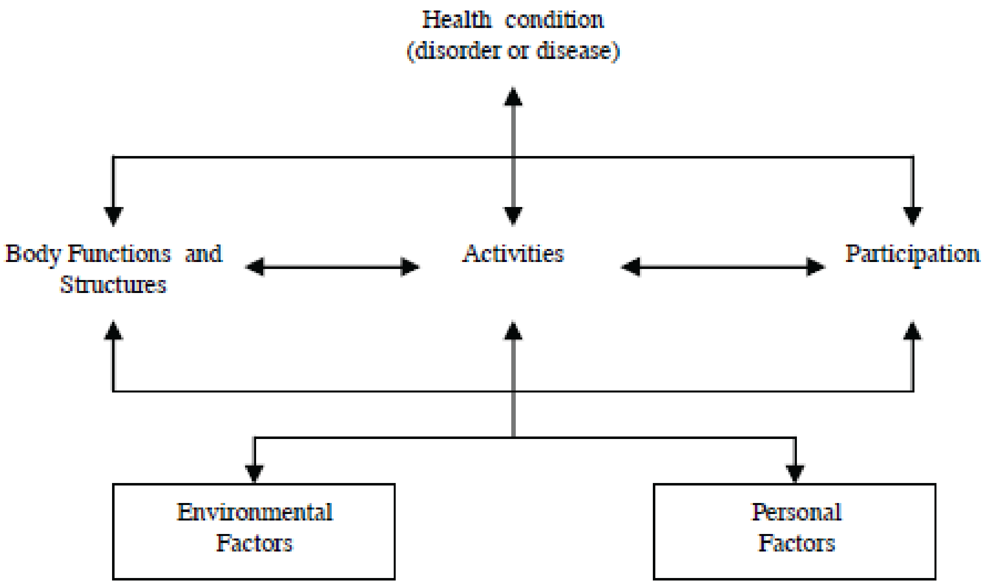

Figure 2: ICF component interactions (Kostanjsek 2011)

The component applicable to the research is Body Structure, as the conditions are likely to result in the use of a wheelchair. Body Structure is sub-divided into eight domains with the following being most applicable to the research:

- 'Structure of the nervous system'
- 'The eye, ear and related structures'
- 'Structures involved in voice and speech'
- 'Structures related to movement'

The ICF has been exploited in a variety of domains. The framework has been used to develop question sets for surveys to collect health and reduced physical ability data, both nationally, e.g. The National Survey in Ireland (Central Statistics Office Ireland 2010), and globally, e.g. the Measurement of Health and Disability in Europe (MHADIE) project (Leonardi 2010). International treaties, initiatives and disability-related national legislations have also been produced using the framework, as well as document assessments of patients' needs for social care (Kostanjsek 2011). Internationally, countries are becoming aware of utilising the framework to determine citizens' levels of disability (Francescutti et al. 2009). The framework has been converted into the ICF Checklist (World Health Organization 2001b) for use in clinical practice to illustrate the functioning of an individual in terms of body functions, activities and environmental factors, and aims to provide a clearer understanding of a patient's health.

The ICF is a useful foundation for the framework to be developed as it classifies the range of disabilities that exist in the different types. It also illustrated that disability should not characterise individuals, which also aligns with the rationale behind the framework. However, the ICF provides a general overview which would be too broad for the framework, hence it is necessary to review further research into disability classification.

Andrews (2014) conducted research analysing the relationship between the ICF, the Downton Scale and impairment types. The Downton Scale maps to the ICF by using three categories: 'Motor control', 'Senses' and 'Cognitive ability', and also links to categories of impairments, as shown Figure 3.

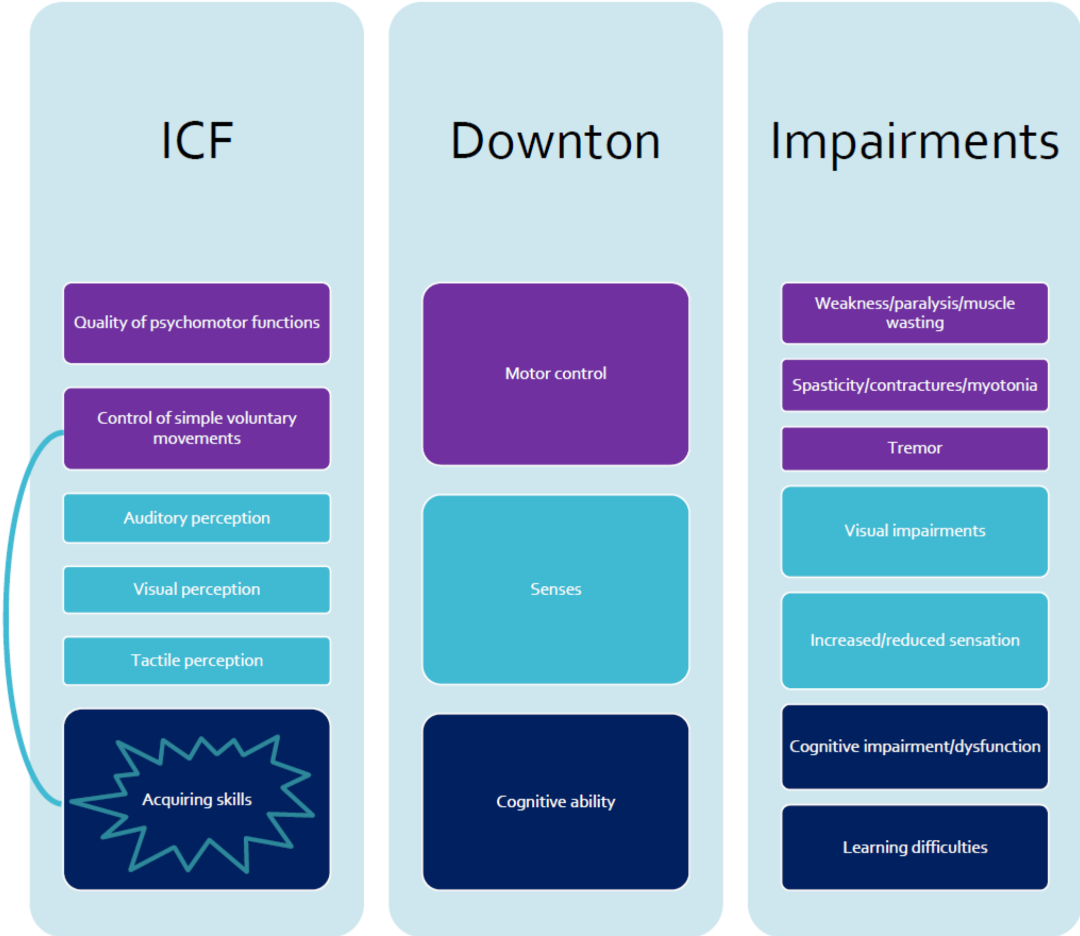

Figure 3: Relationship between ICF, the Downton scale and impairments (Andrews 2014)

The two Downton categories that are relevant to the research are 'Motor control' and 'Senses', as impaired cognitive ability does not result in the use of a powerchair. The impairment types classified as 'Motor control' include Ataxia (reduced neurological co-ordination), paralysis and muscle wasting, contractures in the upper limbs, tetraplegia and quadriplegia. 'Senses' impairment types include visual impairments such as cataracts or abnormal hand sensation. Andrews (2014) identified a set of conditions that resulted in reduced physical ability, which were Acquired Brain Injury, Brittle Bone Disease, Cerebral Palsy, Multiple Sclerosis, Muscular Dystrophy, Osteoarthritis, Parkinson's disease, Spina Bifida, Spinal Cord Injury and Stroke. These conditions can be classified as either Acquired (e.g. a result of trauma) or Congenital (e.g. from birth) and Table 1 summarises Andrews (2014) research by classifying these physical conditions into the categories; 'Neuro-motor', 'Sensory' and 'Cognitive', describes their contra-indications and the recommended input devices and technologies. It is acknowledged that the data in Table 1 provides an overview of common technologies and possible mappings to impairments and physical conditions, with conditions varying in severity. Andrews (2014) identified that the joystick is an input device that can be used by all physical conditions. However, to meet the specific needs of individuals, different types can be used, e.g. a 'golf ball' joystick.

Table 1: Andrews (2014) classification of disability types and the identified input devices

Condition	Classification	Impairment	Contraindication	Suitable Input Devices [1]
Brain Injury	Neuro-motor, sensory, cognitive	Contractures, poor limb control, quadriplegia, visual impairments, cognitive impairments	No reliable movement of any body part, learning difficulties	Standard/golf ball joystick, switches
Brittle Bone Disease	Neuro-motor	Joint hypermobility, dislocation	Increased difficulty performing tasks	Standard joystick, switches
Cerebral Palsy	Neuro-motor, sensory, cognitive	Ataxia, contractures, poor limb control, quadriplegia	No reliable movement of any body part including eyes, severe learning difficulties (lack of understanding of cause and effect)	Standard/T-bar joystick, switches
Multiple Sclerosis	Neuro-motor, sensory, cognitive	Paralysis, weakness and muscle wasting, contractures, quadriplegia, tremor affecting hands, visual impairments, mild cognitive impairments	No reliable movement of any body part including eyes, inability to learn new skills	Standard/T- bar/golf ball/mushroom/ joystick, switches
Muscular Dystrophy	Neuro-motor, sensory, cognitive	Paralysis, weakness and muscle wasting, contractures, cataracts, cognitive impairments	No reliable movement of any body part including eyes	Knob/T- bar joystick, switches
Osteoarthritis	Neuro-motor	Paralysis, weakness and muscle wasting, limited range of movements,	Increased difficulty performing tasks	Knob/T-bar /golf ball joystick, switches

1 See Appendix A for images.

Condition	Classification	Impairment	Contraindication	Suitable Input Devices [1]
Parkinson's disease	Neuro-motor, sensory, cognitive	Dystonia(muscle spasms and contractions), tremor affecting the hands, increased/reduced hand sensation	Inability to learn new skills, dementia, increased difficulty performing tasks	Knob/T- bar/ ball/ mushroom joystick, switches
Spina Bifida	Neuro-motor, cognitive	Paralysis, weakness and muscle wasting	Varying levels of cognitive and physical impairment and learning difficulties	Standard joystick, switches
Spinal Cord Injury	Neuro-motor	Paralysis, weakness and muscle wasting, quadriplegia, paraplegia	No reliable movement of specific body parts	Standard/chin joystick, eye tracking, switches, audio feedback
Stroke	Neuro-motor, sensory, cognitive	Paralysis, weakness and muscle wasting, contractures, visual impairments, increased/reduced sensation in the hands, cognitive impairments, learning difficulties	No reliable movement of specific body parts, inability to learn skills	Standard/T- bar/ball /mushroom joystick, switches

The research performed by Andrews (2014) enhances the ICF and provides further contributions to the framework to be developed. This highlights the variety of impairments that can be contraindications of disability and these would need to be incorporated into the framework. The examples of disabilities and assistive technologies given by Andrews (2014) would be useful to build the foundations for the framework.

Descriptions of each physical condition mentioned in Table 1 are provided in the subsequent sections and classified as acquired or congenital. Poliomyelitis and Motor Neuron Disease are included as these conditions were suggested for inclusion in a framework from Validation Phases 1 and 3 respectively (described in Chapter 9).

2.2.2 Acquired Conditions

Brain Injury can occur after birth, at any point in life and is defined as "a non-progressive acquired injury to the brain with sudden onset" (Headway 2011). There are a wide range of causes of an acquired brain injury, e.g. trauma, brain tumour or haemorrhage, stroke, viral infection or heart attack. The symptoms of the brain injury can vary widely and depend on the location and extent of the damaged brain tissue. There are two types of brain injury; traumatic and non-traumatic, of which a traumatic injury can be classified as open or closed. Open injuries occur when an object enters the brain and typically results in localised damage. A closed injury is caused by the brain moving inside the skull due to an impact, where the brain tissue is stretched or torn. Non-traumatic injuries occur as a result of infectious diseases, a lack of oxygen or tumours.

Motor Neuron Disease (MND) is a rare neurological condition that progressively damages the nervous system (Brain & Spine Foundation 2013) resulting in degeneration of the cells and nerves in the brain and spinal cord that control the muscles (NHS Choices 2017). The condition affects approximately two in every 100,000 people in the UK with 5000 people living with the condition at any one time (Brain & Spine Foundation 2013). Although the condition is not said to be painful, the life expectancy of the individual with MND can be significantly reduced with most people dying within five years of contracting the condition. The symptoms of the condition include muscle wasting and weakness, fasciculations (involuntary muscle contractures), reduced speech ability, swallowing difficulties and muscle cramps (MND Association 2017). The varying forms of MND are Amyotrophic Lateral Sclerosis (ALS) leading to all of the previously mentioned symptoms, Progressive Muscular Atrophy (PMA) that is less common and does not cause muscle contractures, Progressive Bulbar Palsy (PBP) affecting the muscles in the throat, tongue and face resulting in difficulties with speech, swallowing and coughing and Primary Lateral Sclerosis (PLS) that is rarer and only results in contractures and not muscle wasting or fasciculations. Although there is no cure for the condition, Riluzole can be used as a drug treatment to prolong life expectancy by 3-6 months (NHS Choices 2017).

Multiple Sclerosis (MS) affects the central nervous system where myelin (coating around the nerve fibres) becomes damaged. The purpose of myelin is to transmit messages between the brain and the body. The condition affects more than 100,000 people in the UK and can affect three times as many women as men (Multiple Sclerosis Society 2016). The condition causes the body's immune system to mistake myelin for an infection and therefore attacks it. This causes damage to the myelin and removes the nerve fibres that distort the transmission of messages through the nerve fibres. MS has many different symptoms as the central nervous system controls the whole body. The physical symptoms include visual impairments, fatigue, poor balance, dizziness and speech impairments. MS can also affect cognitive ability through emotions and memory loss.

Muscular Dystrophy (MD) is caused by mutations in the genes that define the structure and function of muscles (NHS Choices 2016a). The mutations alter the muscle fibres and therefore inhibit the muscles' ability to function. It is a progressive, inherited genetic condition that gradually causes muscles to weaken over time, resulting in reduced physical ability. The first stage is that a group of muscles is affected, before further groups are also weakened. MD cannot be cured but the symptoms can be managed through treatment. There are numerous different types of MD, with most common being Duchenne, Myotonic, Facioscapulohumeral and Becker. Over 70,000 children and adults have MD in the UK with Duchenne being the most common (NHS Choices 2016). The treatments provided to individuals with MD include mobility assistance, surgery and medication.

Osteoarthritis (OA) occurs when joints in the body become damaged causing lack of joint movement (Arthritis Research UK 2016). The cartilage covering the ends of the bones becomes rough and thin, causing the bone underneath to thicken. A result of this is that the activity of the tissues within the joint increases due to the body attempting to repair the damage. The activity consists of the edges of the bone to grow outwards forming bony spurs and the synovial fluid to thicken and produce an excess causing swelling. The joint capsule and ligaments gradually thicken and contract in an attempt to stabilise the joint. The natural repair process can be successful and therefore, not cause pain or impairments, but in severe OA, the cartilage can become thin to an extent that the ends of the bones are no longer covered. This results in the wear and tear of the bone, displacement and consequent mobility impairment.

Parkinson's disease is a progressive, neurological condition where nerve cells in the body die resulting in a lack of dopamine (Parkinson's UK 2016). The reduced level of dopamine causes slow movements, tremors, rigidity, tiredness, pain, constipation and depression. There is no cure for the disease and it affects 127,000 people in the UK, mainly over the age of 50 (Parkinson's UK 2016). The progressive nature of the condition varies between individuals and the symptoms can be controlled with medication, physiotherapy and surgery.

Poliomyelitis is a viral infection that can now be prevented with a vaccination, therefore, the condition is relatively rare in the UK. It is common to not have any symptoms from the infection; however, a few people may experience high temperatures, sore throats, headaches, aching muscles and nausea that typically last a week (NHS Choices 2016). In less than 1% of cases, poliomyelitis affects the nerves in the spine and the brain, leading to temporary or permanent paralysis, muscle weakness, contractures and deformities. Although there have not been any new instances of the infection since 1984, the research has indicated that people with poliomyelitis contracted pre-1984, experience difficulties in their lives and would benefit from assistive technology.

2.2.3 Congenital Conditions

Brittle Bone Disease or Osteogenesis Imperfecta (OI) is a genetic condition resulting in bones that fracture easily (The Brittle Bone Society 2016). OI is caused by a genetic mutation affecting the production of collagen in the bones and tissues. There are different levels of severity within OI and the symptoms include muscle weakness, curved bones, fatigue and brittle teeth. There are eight types of OI, ranging in severity from mild to potentially fatal (Osteogenesis Imperfecta Foundation 2016).

Cerebral Palsy (CP) is a neurological disorder caused by a brain injury, e.g. at birth (Newsquest Media Group 2004), or a malformation that occurs whilst the brain is under development (Stern Law Group PLLC 2016a). It primarily affects body movement and muscle co-ordination and can have differing levels of severity. There are four classified levels: 'No CP', 'Mild', 'Moderate' and 'Severe' (Stern Law Group PLLC 2016b). 'No CP' is when the individual has CP signs but as the disorder was acquired after the brain had developed, it is classified as the causing incident, e.g. traumatic brain injury. 'Mild' is when the individual can move without assistance and daily tasks are not affected. 'Moderate' requires the individual to have medications, braces and adaptive technology to accomplish tasks. The author has 'Severe CP', as the disorder results in the individual requiring a wheelchair and significant help with daily tasks.

Spina Bifida (SB) is caused by a developmental fault in the spinal cord leaving a split in the spine (Shine 2016). The fault means that the spinal cord has not formed correctly and maybe damaged. The three main types of SB are Cystica, Occulta and Encephalocele. There are two forms Cystica SB: Myelomeningocele and Meningocele, with the first being most serious and common. Myelomeningocele results in paralysis and loss of sensation below a cyst in the spinal cord. The extent of the disability caused by SB depends on the location of the cyst. Bladder and bowel problems can occur with Myelomeningocele SB. The impairments caused by Meningocele SB are less severe although the spinal cord may still be damaged. Occulta is known as the hidden form of SB and is the mildest. Most individuals with Occulta do not present any impairment and it is usually only diagnosed by an un-related x-ray of the back. Encephalocele SB leads to brain damage where the bones of the skull fail to develop correctly.

Spinal Cord Injury (SCI) is caused by traumatic events such as road traffic accidents, violence and falls (Devivo 2012). The results of SCI are irreversible damage such as paralysis and loss of sensation below the injured vertebrae. The loss of sensation below the head is known as quadriplegia/tetraplegia and the loss of sensation on the lower body results in paraplegia. It is more common that males experience an SCI, with the ratio to females being 4:1 (Vercelli and Boido 2014). There can be psychological effects of an SCI both to the individual and families as well as a reduction in life expectancy. The post traumatic care for individuals comes at a considerable cost (Thuret et al. 2006).

Stroke is described as a brain attack that occurs when the blood supply to a part of the brain is cut off, damaging or killing brain cells due to a lack of nutrients and oxygen (Stroke Association 2016). The stroke can cause different degrees of damage and can affect body movement, cognitive ability, sensory perception and communication. There are different types of stroke: Ischaemic, Haemorrhagic and

Transient Ischaemic Attack (TIA). The most common type is Ischaemic, where the blood supply to the brain is cut off by a blockage. Strokes can also be caused by bleeding in or around the brain, known as a Haemorrhagic stroke. A TIA is referred to as a 'mini stroke' where the symptoms last no longer than 24 hours because the blockage is temporary (Stroke Association 2015). The risk of having a stroke increases with age as arteries become narrower and harder. Medical conditions and lifestyles could increase the likelihood of a stroke. As all strokes vary in severity, there are no set recovery times. The sooner that treatment is received lowers the chance of fatality and increases prospects of good recovery.

The review of different types of physical conditions is useful to understand the difficulties that potential users of a framework would encounter in their daily lives. It is appreciated that the conditions summarised above are not an exhaustive list, but the purpose is to provide an overview. It is inevitable that participants involved in the research would have conditions that have not been reviewed and therefore would be investigated when encountered. It is anticipated that the physical abilities of potential users of a framework will vary in severity but will have to cater for individual differences through analysing the abilities that the users are able to perform. The ICF is the international standard for classifying physical conditions and encompasses a broad range of abilities. This needs to be combined with the Downton categorisation scheme to reduce the scope of the possible physical conditions.

In the UK, it is necessary to consider the legal implications of ensuring that people with reduced physical abilities have equal opportunities, as discussed below.

2.3 Equality Act 2010

It is necessary to consider the Equality Act 2010 regarding disability during the research to ensure that consideration is given by a framework to the equal opportunities for people with reduced physical abilities to improve their Quality of Life through utilisation of technology.

The Equality Act was established by the UK government and aims to ensure society is fair in terms of disability by preventing disability discrimination and harassment when providing services or goods to the public. The Act protects any individual who has or has had a physical or mental impairment. According to the Act, an impairment has a 'substantial and long-term adverse effect on the ability to carry out normal day-to-day activities'. Protection is also provided against discrimination due to a disability not possessed by an individual, i.e. being treated less favourably due to having a relationship with a person with disability. This form of discrimination for association was a new addition to the Act, as it was previously covered.

One form of discrimination is direct, where an individual with a disability receives poorer treatment than an individual without the disability, e.g. being denied a service or receiving a compromised level of service. Direct discrimination can also arise from disability and occurs when an individual is treated differently due to an aspect connected with their disability that cannot be justified. The treatment is only justified if it can be demonstrated that it was necessary to meet a legitimate objective in a reasonable way, e.g. the particular training requirements for employment (GOV.UK 2006). A second type of discrimination is indirect, which can occur when there is a rule that applies to all individuals but particularly disadvantages people with disability and no reasonable adjustments have been made. Reasonable adjustments are a legal requirement to make changes to ensure that people with disability provide an equal level of service. An example would be performing structural changes to building to improve accessibility. Other forms of discrimination protected by the Act are harassment and victimisation. Disability harassment is the unnecessary behaviour associated with disability that has the sole purpose of intimidating, humiliating or offending a person with disability. Victimisation can occur following a complaint made under the Act, where the individual is subsequently treated unfairly. The Act states principles of good practice that public services should adhere to, including informing staff of accessibility requirements, providing disability related training of staff, consulting customers with disability about the equality of services and reviewing the accessibility of services regularly.

It is essential that a framework adheres to the Equality Act to ensure that it provides equal opportunities regardless of an individual's specific ability. The definition of an impairment by the Act refers to "ability" which aligns to the rationale behind a framework. To align with the discrimination aspects of the Act, the framework must cater for all physical conditions so that all users are able to obtain technology recommendations. The recommendation provided can be considered as reasonable adjustments to allow people with disability and equal level of service. As a method of characterising physical abilities, Range of Movement (ROM) is described in the subsequent section.

2.4 Range of Movement (ROM)

ROM is a measure of movement about the axis of a joint (Kielhofner 2006), as illustrated in Figure 4. There are two methods of measuring ROM; Active and Passive. Active ROM involves an individual moving a joint themselves whereas Passive occurs when the joint is moved by a third party without assistance of the individual (Edugyan 2013). Full ROM implies that a joint can be moved in all directions permitted and therefore, has good flexibility provided by ligaments, tendons, muscles and bones. However, conditions can reduce the ROM of a joint such as osteoarthritis, pain and swelling as well as injuries resulting from traumatic events. The age and activity level of an individual can also be a contributing factor to the ROM. The type of ROM applicable to the research is functional ROM that is the minimal motion necessary to comfortably and effectively perform the activities of daily living (Vasen et al. 1995). This has been identified as being an accurate and precise, measurement of disabilities and impairments, where it is realised that individuals with limited ROM will adopt compensatory motions and methods to accomplish their daily tasks (Vasen et al. 1995).

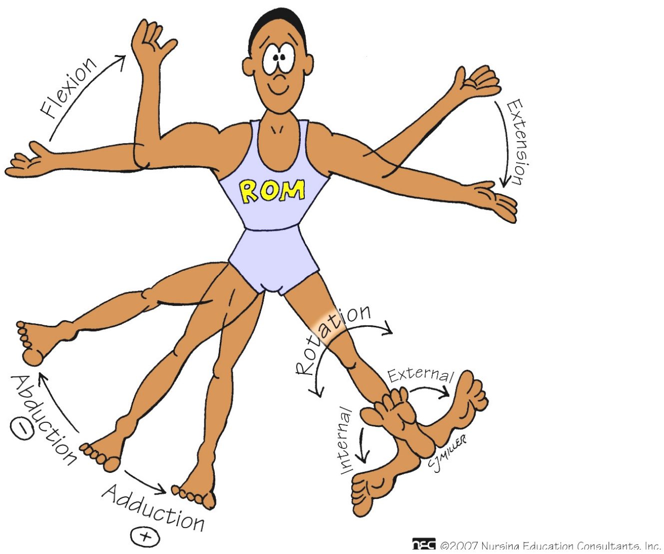

Figure 4: Types of Range of Movement (CS Health & Fitness 2017)

Historically, ROM was measured through observation but was subjective to the examiner. Currently, the main method of accurately measuring ROM is to use a goniometer, and instrument that measures the angle of a joint from between 0 and 180 or 360 degrees, depending on the type of joint being measured. As an example, a goniometer can be used to measure knee flexion where the centre of the instrument is placed alongside the joint and the arms of the goniometer align to the angle of the legs above and below the knee. Bending the knee provides a measurement of the movement. In recent times, pervasive technologies have been developed such as the Microsoft Connect Sensor and Leap Motion Controller that offers greater accuracy than a goniometer (Pham et al. 2014).

The Washington State Department of Social and Health Services (DSHS 2014) developed a measuring chart to state the anatomically normal ROM for all parts of the body. The applicable aspects to the research are the movements of neck rotation, shoulder flexion, elbow extension, wrist flexion, and extension, finger flexion and ankle plantar flexion, as these are the movements required to interact with technologies. Shoulder movements have been shown to be fundamental to performing daily activities through the functional assessments using the American Shoulder and Elbow Surgeons' Shoulder Score (Richards et al. 1994), the Penn Shoulder Score (Leggin and Iannotti 1999) and the Simple Shoulder Test (Lippitt et al. 2006). The tasks in the assessment included placing a can of soup on an overhead shelf and reaching a shelf above a head without bending the elbow. It was shown that functional tasks could be completed without full shoulder motion i.e. between 57% and 76% of full motion (Namdari et al. 2012). In conjunction with the shoulder, elbow movements are necessary for positioning the hand in space during the activities of daily living (Pham et al. 2014), where the functional movement is between 30 and 130 degrees. Finger and wrist movements are important for many dextrous daily activities and are determined by fingertip trajectories that can be used to measure dexterity. The set of possible finger positions for the user can be referred to as 'the reachable space'. Neck rotation is relevant for interaction with technology that requires the user to rotate 80 degrees left or right. The only relevant ankle movement is plantar flexion, as technology would rely on a downwards movement of the ankle, i.e. to operate a switch.

It is apparent that Active functional ROM can be an effective method of determining the ability of a user in terms of the movements that can be performed independently, thus Passive ROM would not be relevant. Active ROM provides a greater understanding of the actions that users can perform than disability type. However, it would not be practical or necessary to accurately measure a user's ROM using a goniometer for a framework, as the ROM can be measured through observation to determine whether a user can or cannot perform movements. The measuring chart developed by

DSHS (2014) can be adopted as an aid to inform the types of ROM to be considered for a framework.

The review of physical conditions identifies the consideration to be made within the Human aspect of a framework. As the framework also relates to the Computer (through technologies) and Interaction aspects (through a variety of mediums), the domains of Human Computer Interaction (HCI) and multimodal interactions are highly applicable to be reviewed.

2.5 Human Computer Interaction (HCI)

As the research domain is primarily HCI, it is important that users are considered during the design process of a framework by applying the globally recognised principles of Ergonomics of human-system interaction (ISO 9241-210:2010, previously known as Human-centred Design), Universal Design (Park et al. 2014) and Design For All (Barnes 2011).

2.5.1 Ergonomics of Human-system Interaction

The Ergonomics of Human-system Interaction concept was formally recognised as Human-centred Design, which was first defined at the University of California in San Diego by Norman and Draper (1986). It is now included in the Ergonomics of human-system interaction ISO standard relating to Human-centred Design for interactive systems. To achieve this, it is essential to involve potential users in both the design and development of the system. Preece et al. (2015)

recommended background interviews and questionnaires involving users to be completed at the start of the design process to collect data relating to their requirements and expectations. In the early stages of the design process, work interviews, focus groups and on-site observations should be conducted from stakeholders. These should discuss issues concerning the environment in which the system is to be used, system requirements and the work sequence that will be completed with the system. During the mid-stage of the design process, role plays, walkthroughs and simulations of prototypes should be completed to evaluate designs and elicit additional requirements. The final phase of the design process should involve collecting quantitative usability data by conducting usability testing and qualitative user satisfaction data through the completion of further interviews and questionnaires.

Norman (2002) states four recommendations for placing the user at the centre of the design:

- "Make it easy to determine what actions are possible at any moment.
- Make things visible, including the conceptual model of the system, the alternative actions, and the results of actions.
- Make it easy to evaluate the current state of the system.
- Follow natural mappings between intentions and the required actions; between actions and the resulting effect; and between the information that is visible and the interpretation of the system state." (Norman 2002, p.188)

Seven principles of design were also created to ensure that designers assist the user with performing tasks. The principles can be simplified to:

1. Writing understandable operating manuals.
2. Simplifying the structure of the tasks to avoid short and long term memory overloads.
3. Making it obvious which operations need to be performed.
4. Making the relationships between interactions and actions, actions and effects and the state of the system understandable.
5. Constraining the design so that it meets the purpose.
6. Planning for every possible error that could be made to ensure that the user can always recover.
7. Ensuring that a universal standard is developed when the process can be completed logically.

Following a Human-centred Design process has an advantage of gaining a greater understanding of the social, ergonomic, organisational and psychological factors affecting technology. The process also ensures that the system could be suitable for the intended users and environment. A research report by Project Management Solutions (2011) states that badly defined system requirements is the top cause of failed Information Technology projects. Implementing a Human-centred Design has the benefit of avoiding these mistakes and leading to increased user satisfaction. Additionally, the involvement of users in the design process can result in the development of improved specialist equipment and the inclusion of people with disability (Newell et al. 2010).

The ISO standard for Ergonomics of human-system interaction (ISO 9241-210:2010) in relation to human-centred design for interactive systems can be illustrated in the framework diagram in Figure 5, which demonstrates the iterative process that is followed to design a solution to meet the user requirements.

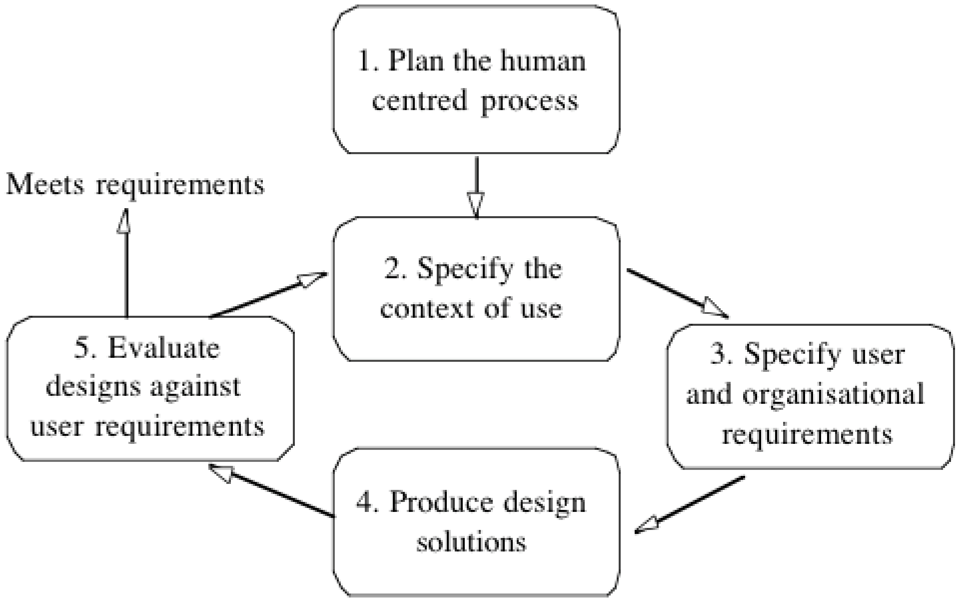

Figure 5: ISO Human-centred design Framework (Innovator's Guide Switzerland 2017)

The first stage is to understand the context of use in order to generate user requirements. The requirements are then utilised to produce design solutions that can be evaluated against the user requirements. The iterative nature of human-centred design is produced by the involvement of users during the design process, which could lead to modifications to the design of the system.

The review of the ISO standard for Ergonomics of Human-system Interaction highlighted the methods that need to be adopted in order to adhere to the standard. In particular, interviews and focus groups could be potential activities to conduct to elicit requirements and validate findings. Simulations and walkthroughs could be performed to elaborate the usability of technologies, resulting in the collection of qualitative and quantitative data. The recommendations defined by Norman (2002) can be considered during the development of a new framework to ensure that users can understand the purposes of the sections as well as the holistic view of the framework. To maximise the exploitation potential of a framework, the principles of design also stated by Norman (2002) should be addressed. Most notably, ensuring that the design meets the purpose, planning for errors and constructing the framework in a format that is logical. To achieve a human-centred design process, it will be imperative that users are involved during the design of a framework to understand their requirements and to validate aspects. This would ensure that the framework achieved the key contribution of the research.

This concept is the main rationale behind a framework, as the aim is to recommend technology solutions to suit the abilities of the user. The context of the use of a framework is established early in the design process through requirements elicitation from people with reduced physical ability to ensure that a framework is established that is suitable for the assistive technology domain. The framework evaluation is conducted through validations involving people with reduced physical disability and experts from the domains of healthcare and technology. The framework design may subsequently be revised to incorporate their views and further evaluated needed to ensure the user requirements are met.

2.5.2 Accessibility (Design For All)

Accessibility or Design For All is a further aspect to be considered during the development of a framework. In order to design for human diversity, social inclusion and equality, ensuring that all people have equal opportunities of participation in society regardless of age, gender, racial ethnicity and ability, the Design For All principle was introduced in the European Institute for Design and Disability (EIDD) Stockholm Declaration in 2004 (EIDD 2009). The concept of Universal Design states that the design of products and environments should be usable by all people (the elderly, pregnant women, people with reduced physical ability, children and people with obesity) without the need for adaptations. The inclusion of the standard is not essential but it is important that the design is universally suitable. To achieve Universal Design, the intended user community should participate in the design process. It is the responsibility of the designer to include potential users and to identify user groups that are not included in the design process.

Design For All contributes to the global commitment of a Society For All and is supported by other similar contexts as Inclusion Design, Conception Universelle in France and Design d'utenza ampliata in Italy. Eight criteria are stated as part of the principle:

- Respectful - the diversity of users should be respected without marginalisation.
- Safe – users should be free of risk.
- Healthy – no health risks are posed on the users and healthy concepts should be promoted.

- Functional – the intended functions should be performed as intended and do not present additional difficulties.
- Comprehensible – clear information should be presented using well-recognised icons and a clear layout should avoid confusion.
- Sustainable – the unnecessary use of natural resources should be forbidden.
- Affordable – all users should have the opportunity to use the design.
- Appealing – the design should be socially acceptable.

These criteria are supported by the seven principles of Universal Design defined by researchers, architects and engineers at the Centre for Universal Design at North Carolina State University (Snider and Takeda 2008):

1. Equitable Use – the design should be useful and marketable for a range of reduced physical abilities.
2. Flexibility in Use – the design should accommodate the preferences and abilities of different users.
3. Simple and Intuitive Use – the design should be easy to understand whatever the experience, knowledge, language or concentration level of the user.
4. Perceptible Information – the required information should be communicated efficiently to the user in all ambient conditions, regardless of the user's sensory ability.
5. Tolerance for Error – the results of unintended actions should be minimised by the design.

6. Low Physical Effort – the user's fatigue should be minimised by a design that can be used comfortably.
7. Size and Space for Approach and Use – irrespective of the mobility, posture and body size of the user, the necessary size and space should be provided for approach, reach, manipulation and use.

The rationale behind Universal Design is that 'everyone is affected' and the 'design affects everyone' (Snider and Takeda 2008). The costs of creating a Universal Design can be high, but the failure to successfully create is equally as costly. The success of the principle is reliant on the education of the public to understand the principles and the benefits that can be obtained.

An advantage of Universal Design is that it can promote independent living through design solutions that are accessible to users with any level of ability. In some situations, Universal Design can determine the extent to which an individual remains independent. Design For All cannot always be achieved by a single solution that suits all users. The design should be adjustable, so that different functional requirements can be met, e.g. an office chair that is adaptable to fit many different users (Ergonomic Seating Solutions 2016).

The design of a framework needs to include aspects from both Design For All and Universal Design. The rationale behind a framework is to 'Design For All' by providing technology recommendations to suit individual abilities. The criteria of the principle will be useful to consider when evaluating interaction mediums and technologies for inclusion in a framework. The most relevant criteria being "Safe" (to ensure that users are not exerted to unnecessary additional risk due to technologies), “Functional” (the technologies must enable the necessary daily activities to be performed efficiently), “Affordable” (the cost of the individual technologies will be a determining factor for inclusion in a framework) and “Appealing” (the technologies must not draw attention that the user has reduced physical ability). The Universal Design criteria also provides factors that could be measured during the evaluations of technology. It will be important that any technology is simple and intuitive to use regardless of the experience and knowledge of the user with reduced physical ability. Secondly, that interactions with the technologies should not exert significant unnecessary physical effort on the user.

A Human-centred design approach ensures that a framework has maximum potential to assist users in their daily lives with interactions that otherwise would not be possible. When users are provided with a range of mediums (depending on their abilities), which can be viewed as multimodal interactions with technology and require definition.

2.6 Multimodal Interaction

Oviatt (2003) defines multimodal systems as “those that process two or more combined user input modes in a coordinated manner with multimedia outputs”. The rationale behind this form of interaction is to offer alternative channels for users or providing interaction that can use two or more modalities concurrently. The natural method of interaction with the world is multimodal, as humans are able to utilise the five major senses of sight, hearing, touch, smell and taste to explore environments and obtain information (Turk 2013).

However, traditionally HCI has been thought to be unimodal, where users interact through a single channel, e.g. a keyboard. It is actually multimodal as users interact with a variety of devices such as a keyboard, mouse and display. Due to advances in hardware and software, multimodal systems are emerging where humans are able to communicate through natural interaction methods including speech, touch and gesture (Pfleging et al. 2012).

Multimodal interaction was described by Van Dam (1997) as a 'post-WIMP' computing environment that moves beyond interfaces consisting of Windows, Icons, Menus and Pointers, as in a conventional Graphical User Interface (GUI). It is recognised that the first demonstration of multimodal interaction was the 'Put That There' system developed by Bolt (1980) that enabled the user to experience natural and efficient voice and gesture interaction with a wall display, as shown in Figure 6. The next significant example was by Koons et al. (1993) who developed a map-based application that integrated speech, gesture and eye gaze interaction. In 1997, the QuickSet simulator for the US Marine Corps was an example of a multimodal pen and voice system that operated on an early tablet Personal Computer (PC).

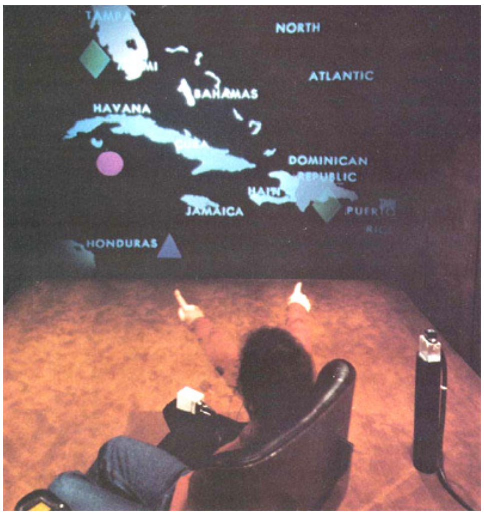

Figure 6: Voice and gesture interactions with Bolt's 'Put That There' system (Bolt 1980)

The advent of smartphones brought an illustration of multimodal interaction as the device could be operated via different methods including speech and the recent introduction of 3D vision sensors. A modern example of multimodal interaction is with vehicles, where information and entertainment systems can be controlled through a variety of modalities, for example navigating a hierarchical menu using buttons and controlling entertainment through speech commands or gestures. Pfleging et al. (2012) identified challenges when designing multimodal systems for vehicles including the learnability (the ease of remembering commands), visibility (the knowledge of the recognised commands) and facility to undo actions. It is therefore, important to consider these aspects when designing successful multimodal systems.

There have been several examples of multimodal devices being used as assistive technologies. Kunze et al. (2014) conduct an explorative study whereby a head-mounted display is trialled with older adults to see whether the user group can benefit from wearable computing. It was concluded that older adults could benefit from a head-mounted display although there were practical complications with the navigation requiring a swiping gesture and that the menu structure could be overly complex for older users. However, these difficulties could be resolved by the users' operating the device for the alternative voice modality. In a study by Miller et al. (2017), Google Glass have been investigated to ascertain whether the device could assist students who are hard of hearing in lectures. A sign language interpreter was displayed on the Glass instead of on a separate monitor. The participants found that having the smartglasses reduced the amount of head movement required during a lecture, as it was possible to view the interpreter and the lecture slides simultaneously, thus improving their concentrating on the lecture. Google Glass provides multimodal interaction by having both touchpad and voice inputs and a study by Malu and Findlater (2014) compared the usability and comfort of the two modalities from participants with cerebral palsy. It was concluded that more than half of the participants were not able to use the touchpad input, but could benefit by operating the device through voice commands. Another example of multimodal interaction for users with reduced physical ability is the PaeLife Personal Life Assistant (Teixeira et al. 2014) that enables older adults to interact with the assistant via gestures or speech to access online services including messaging, calendars, social networks or real-time information such as weather.

These examples demonstrate that multimodal interaction can benefit people with reduced physical ability as alternative modes of interaction are provided to cater for individual abilities. This increases the number of users that can potentially benefit from the technology compared to traditional unimodal devices. Hence, this is an important aspect to consider for a framework that represents technologies based on the user abilities. As it has been shown that smartglasses can provide multimodal interaction that benefits the user community, these devices will be investigated in a feasibility trial.

The aim of multimodal interaction is to support the two-way communication between humans and machines by offering improved flexibility and reliability. However, multimodal systems are yet to be as widely recognised in computing compared to unimodal interaction due to additional challenges including the interoperability between technologies. To assist development, Reeves et al. (2004) defined a set of guidelines for the design of multimodal systems. The guidelines stated that the system could be designed for the broadest range of users, to maximise human and cognitive and physical ability and adapt to meet the needs of users with differing abilities and individual differences. These guidelines and the other principles of multimodal interaction are relevant to the development of a framework to maximise the types of physical conditions that benefit from the produced recommendations. To further understand the modality of interaction that is provided by individual technologies that network together to achieve the goal of assisting a user, a System of Systems (SoS) approach can be adopted during the development, as explained in the next section.

2.7 System of Systems (SoS)

Systems Engineering is a diverse area that encompasses hardware, software and human systems. Since the late 1990s, System of Systems Engineering (SoSE) has been an evolving area of research. The main difference between traditional Systems Engineering and SoSE is that Systems Engineering concentrates on building the right system whereas SoSE aims to develop the right combination of systems to satisfy a complex set of requirements. SoSE research has been driven by the growth of global issues including energy, transportation, population growth and security. A SoS can be analysed using techniques including Characterisation of SoS and the Capability Cube Model.

2.7.1 Defining SoS

In general, SoS is viewed as a system that contains two or more independently managed elements (Hitchens 2009), however, from a technical perspective, a SoS is defined as an "an integration of a finite number of constituent systems which are independent and operable, and which are networked together for a period of time to achieve a certain higher goal" (Jamshidi 2009). The complexity of a SoS determines the changeability of the system and is the result of relationships becoming established between constituent systems, which can either be static or dynamic (Sommerville 2014). Static relationships are planned and can be anticipated through analysis of a SoS (e.g. a 'uses' relationship in a use case diagram), whereas dynamic relationships only exist during execution of the SoS (e.g. a 'calls' relationship in programming code that will be executed depending on the state of the SoS). A SoS typically has the following characteristics described by Maier (1998); operational and managerial independence of constituent systems, emergent behaviour, evolutionary development and geographical distribution of constituent systems. Operational independence implies that each constituent system should be independently functioning, whereas managerial independence states that constituent systems should be controlled by different owners and therefore, are operated independently. Constituent systems are seen as being heterogeneous as they typically are designed using varying design styles and programing languages. Emergent behaviour indicates that the capability of the entire SoS should not be possessed by any constituent system and the behaviour of the SoS can only be provided by the interactions between the constituent systems. There are often differences between the roles of the constituent systems and the SoS, e.g. in terms of stakeholder involvement, performance and behaviour and testing and evaluation. It is important to learn the environment in which the SoS will be applied so that the correct development principles can be adopted. A SoS should not be created 'once for all' but should evolve through the development by the addition, modification or removal of constituent systems. Geographical distribution highlights that a SoS can be dispersed through a wide geographical area and often leads to the need for an externally managed network, e.g. constituent systems being located in different countries communicating as a single SoS. A SoS is also seen as data intensive that usually relies on the management of large volumes of data.

There are four types of SoS suggested by Maier (1998), Dahmann and Baldwin (2008); Directed, Acknowledged, Collaborative and Virtual. In a Directed SoS, the constituent systems are able to operate independently but their usual method of operation is interacting through a SoS. An Acknowledged SoS comprises constituent systems that are maintained independently, but the overall SoS has an assigned central management authority. Alterations to the constituent systems are only permitted with an agreement between the authority and the constituent system. Constituent systems have greater control in a Collaborative SoS and can interact independently to meet the objectives of the SoS. Providing or denying service to the constituent systems maintains the operating standard of the SoS. A management authority is not required in a virtual SoS as invisible mechanisms are used for maintenance. This can lead to a variety of behaviours from the constituent systems that may be of benefit to the SoS purpose.

The concept of a SoS was initially developed for the defence industry, but is now applied to other domains such as education, transportation, healthcare, disaster response and energy. An example of a disaster response SoS is an emergency information system that integrates information from the police, ambulance, fire and coastguard to manage emergencies such as flooding and accidents (Sommerville 2014). A second example within the education domain is the iLearn digital learning environment that is utilised by schools in Scotland. The environment assists students with their education but is connected to school administration and network management systems that protect the safety of the students online through internet filtering services.

Figure 7: The management user interface of the iLearn digital learning environment (iLearn Inc. 2017)

It is evident that the framework to be developed will be a SoS consisting of constituent systems in the form of technologies that can assist people with reduced physical ability. As the framework would not be a traditional form of SoS, not all of the characteristics defined by Maier (1998) are relevant. The operational independence of the constituent systems would be appropriate as the technologies can perform independently, however, the geographical distribution of the systems would not be applicable due to being focused in a small area surrounding a user. It will be important to consider an evolutionary development of the SoS to ensure that a framework can cater for technologies that are available in the future. This framework can be seen as a Directed SoS as any technologies to be included can operate independently, but could only provide assistance to the user when operating as an SoS. The alternative types of SoS are not relevant due to a management authority not being required. The development of a framework and concept demonstrator are therefore considered to be within the domain of SoSE as both are involved in the integration of existing systems to create new functionality and capabilities (Sommerville 2014). To enhance understanding of the SoS created by a framework and concept demonstrator, characterisation and description techniques need to be applied.

2.7.2 Characterisation of SoS

Characterisation and description of SoS is a theme suggested in the Trans-Atlantic Research and Education Agenda in System of Systems (T-AREA-SoS), a project funded by the European Commission to establish a strategic research agenda for SoSE (Henshaw 2013). The theme addresses the practicalities of engineering SoS and thereby defines the focus of the engineer's interest and activity to describe a structure and operational behaviour of a SoS for the intended and emergent cases. The aim of the theme is to fully understand the SoS concepts and to improve the feasibility of technology insertions. Within this theme, four problem areas have been identified; elucidating a coherent characterisation of SoS including the boundaries and goals, establishing common terms and definitions, understanding the consequences of the interaction between components and the characterisation of governance structures. To elicit a coherent characterisation, it is necessary to consider more attributes other than System of Interest (SoI) to create a general understanding across different stakeholders. The T-AREA-SoS established a thesaurus for SoS to define the common terms and definitions (Henshaw 2013) to improve the collaboration between the different stakeholders within SoSE. It was seen to be important to analyse the interactions in a SoS to reduce the risk of a SoS failing due to inadequacy with the interoperation between constituent systems. The characterisation enabled improved design of interactions by achieving a greater understanding prior to implementation of the SoS. The final problem area of governance structures seeks to reduce the risk of failure due to discrepancies between organisational structures, e.g. the cancellation of information technology projects (Barot et al. 2012). The area recommends control measures to be adopted when acquiring and operating constituent systems.

Characterisation and description of SoS provides a holistic view of the framework and concept demonstrator components and their interactions. The areas of the Characterisation of SoS that are most relevant to the research are the consequences of interaction between components and understanding the boundaries of the SoS. These can be applied to the concept demonstrator to ascertain the systems that are considered to be included in the SoS. These techniques will improve the understanding of the concept demonstrator prior to conduction of the feasibility trials and evaluation. To further increase comprehension of the specific constituent systems of the concept demonstrator, System of Interest (SoI) analysis is necessary to be undertaken.

2.7.3 System of Interest (SoI)

One definition of the SoI of a system is "the system whose lifecycle is under consideration" (INCOSE 2017), however, there is no consideration of the resultant behaviour of the SoI. The behaviour is caused by the interactions between constituent systems, without which the SoS would be a set of independent systems. The SoI Framework developed by Kinder et al. (2012) is a top-down approach to define the interactions both at generic and specific levels to identify the interaction mediums and types. The framework describes the lifecycle or evolution of the SoS and the constituent systems, which defines the dynamic attributes of a SoS. Other attributes considered are the variability (frequency of change and stability), functions required to achieve the purpose of the SoS, systems owners and operations (the relationships between the stakeholders in the SoS) and the concept of operations, use and employment (for the entire SoS and not the constituent systems).

To fully analyse the concept demonstrator for a framework prior to development, SoI can be combined with Characterisation of SoS to provide a greater understanding of the capabilities and functions. Generally, the design process of a SoS is challenging compared with traditional system design (Keating and Katina 2011), as the individual architectures of the constituent systems have to be considered, which can lead to differing or incompatible assumptions being made by the developers of the constituent systems (Sommerville 2014). Combining the constituent systems causes risks such as unintended resultant behaviour that does not occur when the systems are individual. A SoS is described as developing and evolving (SEBoK 2016b) and to ensure the adaptability and interoperability of the SoS, two approaches can be applied: Open Systems and Architecture Patterns. The Open Systems approach (Azani 2009) contains eight principles including Open Interface, Synergism, Reconfiguration, Symbiosis and Modality, whereas Architecture Patterns are represented by a three-layered stack model encompassing operational, systems and component elements. The stack relates to an analysis approach that describes the SoS at systems architectural and design level through the categories: architectural, interaction and design (Kalawsky 2015).

The boundaries between each constituent system should be permeable to allow for data exchange, whereby the Open Interface Principle relates to the operational layer (the highest level of abstraction defining the overall system architecture) or the architectural analysis category. The principle of Synergism also relates to the operational layer as it states that the combined interaction between constituent systems has greater effect than the interaction of the individual systems. As Synergism describes the interaction of the SoS, it can be included in the Interaction analysis category. The Reconfiguration and Symbiosis Principles concern the systems layer of the stack (describing the implementations of the independent sub-systems), as the constituent systems should be adaptable to the environment and able to collaborate with each other to achieve the goal of SoS. The lowest level of the stack describes the constituent system architectures that should meet the Modality Principle where each system operates independently. Therefore, these three principles concern the design analysis category.

An advantage of implementation using an Open Systems approach is that the process of enhancing the capabilities of the SoS is improved through having modular systems, as the constituent systems can be easily upgraded (Henshaw et al. 2011).

SoS can be applied to two instances in the research, the concept demonstrator and framework to improve understanding. It would be insufficient to only conduct either Characterisation SoS or SoI singularly, as each technique elicits differing information regarding the SoS. The first technique elicits in-depth technical details concerning the constituent systems, whereas the latter allows conceptual aspects to be identified such as sustainment and support. The constituent systems in a framework SoS consist of 'off-the-shelf' technologies that may either be generic or specific assistive technologies. Further descriptions of the assistive technology domain and the relevant individual technologies are provided.

2.8 Assistive Technologies

An assistive technology can be described as "any product or service designed to enable independence for disabled and older people" (Williams-Zahir 2015). Although some of the technologies are specifically designed for this user community e.g. powerchairs, the

Automated Transport and Retrieval System (ATRS) and SmartATRS, other technologies that can be utilised as assistive technologies e.g. electroencephalograph (EEG), Tracking Learning Detection (TLD), iOS Switch Control and smartglasses are described.

2.8.1 Powerchairs

Powerchairs (also known as powered wheelchairs, Figure 8) can be defined as, "wheelchairs propelled by means of an electric motor rather than manual power" (Disability World 2016b) and are an assistive technology providing independence for users with mobility restrictions. Prior to the development of powerchairs, manual wheelchairs were the only solution providing a means to achieve locomotion but required physical effort to be exerted either by the individual or a carer. Advances in manual wheelchairs have seen the advent of specialised wheelchairs including those for sport and beach environments (Gaba et al. 2016). Sports wheelchairs have been developed for competitors in football, rugby and tennis featuring streamlined seats with robust frames, whereas wheelchairs designed for utilisation on a beach have larger tyres able to negotiate sand and water. These wheelchairs are available in tourism resorts, e.g. Borough of Poole (2016), to provide equal leisure opportunities for people with reduced physical ability.

Figure 8: An Invacare TDX SP Powerchair (Gerald Simonds Healthcare Ltd. 2017)

Butler (1986) states that independent mobility is critical to individuals of any age, as it allows them to achieve their vocational and educational goals. However, some people with reduced physical ability, such as those with Multiple Sclerosis (MS), either experience difficulty in operating a standard powerchair or find it impossible (Srivastava et al. 2014). Recent developments in technology have led to the concept of a SmartPowerchair. Postolache et al. (2009) describe the UbiSmartWheel which is considered a 'smart' wheelchair that creates a pervasive biomedical assistive environment for the elderly. The powerchair contains systems to measure physiological parameters of the user including heart and respiratory rates. Users are remotely monitored and therefore the UbiSmartWheel is seen as a type of telemedicine. The powerchair is implemented as a client server device with the powerchair as the server. The healthcare workers are the web clients and access the users' physiological information which is automatically updated either when the sensors take a measurement; the user is detected in the powerchair for the first time or after the user has been away from the powerchair. The healthcare workers can also see the location of the powerchair by using the data sent from the Radio-frequency Identification (RFID) tag attached to the powerchair. The UbiSmartWheel is seen as an unobtrusive and reliable method to monitor vital signs of a powerchair user, whilst decreasing administration costs and improving quality of care. The important aspect of the powerchair is that no user interaction is required to measure their vital signs.

Another example of a SmartPowerchair is the Intelligent Powered Wheelchair (Mihailidis et al. 2007) which is designed for older adults with cognitive conditions that would adversely affect their ability to navigate the powerchair. The Intelligent Powered Wheelchair combines artificial intelligence with user preference to determine the actions to take and aims to ensure safe navigation and promote mobility and exploration. A 3D infrared laser sensor is mounted to the front of the powerchair to monitor the upcoming environment. The wheelchair communicates with the user verbally to determine the direction in which to navigate. There is also an anti-collision system which is able to detect objects, prevent collisions and activate the user's preference in negotiating obstacles. The limitations of the Intelligent Powered Wheelchair include; small objects being less likely to be detected and the accuracy of the navigation which is reduced in restricted light conditions, such as darkness, reflections and emission sources (e.g. sunlight).

SmartPowerchairs have been developed that can be controlled by a non-invasive brain signal interface control (Iturrate et al. 2009), where navigation is achieved through the concentration of the user. Visual stimulation is used to elicit EEG signals to obtain the user's desired location and to autonomously drive the powerchair, whilst avoiding obstacles detected by a laser scanner. This system provides greater accuracy without the need for long-term training. The necessity for a user to continuously concentrate on the task is potentially a disadvantage, while the complex processes required for the EEG signals, through multiple microprocessors, increases the cost of the powerchair.

Voice and vision are also interaction mediums used to control SmartPowerchairs (Prabitha et al. 2012). Voice-operated systems can assist users who have reduced limb abilities and can be achieved by a voice recognition integrated circuit which accepts voice commands from a user before conversion into signals for a microcontroller to process. The output is the desired direction of the powerchair. Vision-based control systems for powerchairs can incorporate integrated two webcams, one facing the user to detect eye movements through electrooculography and a second positioned forward to identify obstacles (Bailey et al. 2007; Ubeda et al. 2011). A disadvantage of vision-based systems is the reliance on the user continuously looking at the webcam to determine direction and therefore is not able to concentrate on other tasks.

Interaction through head gestures is a further example of an alternative method to control a powerchair. Srivastava et al. (2014) describe a dual control system applied to a 'Smart Wheelchair' that contains multimodal interactions of voice and gesture by integrating a voice module, an accelerometer[2], ultrasonic sensor and a display with a powerchair. The voice recognition module receives speech input from the user and sends the corresponding commands to the powerchair controller. The gesture recognition operates in a similar way where input to the accelerometer, consisting of voltage variations depending on the tilt of the user's head, is transmitted to

[2] An electromechanical device that measures acceleration forces.

the controller. Voice commands are recognised by the system following a training and testing phase where words are defined in a dictionary and recognised using a classification algorithm. The 'Smart Wheelchair' is perceived to be advantageous for users with reduced hand, leg and eye movement, who are not able to operate a powerchair through a standard joystick interface.

The advancements from manual wheelchairs, to powerchairs and the recent SmartPowerchairs contribute to increasing Quality of Life for people with reduced physical abilities through independence which would otherwise not be possible. The review of the current state of the art concerning powerchairs identifies the types of technology that have previously been integrated into powerchairs to enhance the usability for people with reduced physical ability. However, these powerchairs only assist the user with navigation and not other daily activities. The technologies to be incorporated into a framework would need to assist with other activities as well as being suitable for potential integration into powerchairs. A further example of a vision-based controlled SmartPowerchair is within the ATRS, an alternative mobility solution consisting of robotics to transport a powerchair in a vehicle. ATRS is the research case study, which will be further described in the following section.

2.8.2 Automated Transport and Retrieval System (ATRS)

A form of assistive technology is Automated Transport and Retrieval System (ATRS), introduced in Section 1.1 as the case study for the research through SmartATRS. Originally developed in 2008 by Freedom Sciences LLC in the United States of America (USA), this technically-advanced system featured in New Scientist magazine (Kleiner 2008). Gao et al. (2008) stated that the overall objective of developing ATRS was to create a reliable, robust means for a wheelchair user to autonomously dock a powerchair onto a platform lift without the need of an assistant. ATRS requires the vehicle to be installed with three components; a motorised seat that rotates and exits the vehicle through the driver's door, an automated tailgate and a platform lift fitted in the rear of the vehicle.

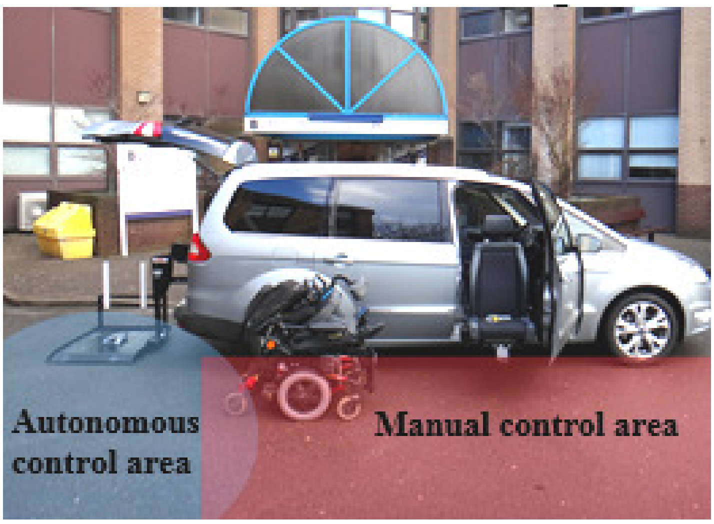

Figure 9: ATRS operating zones

Using a joystick attached to the driver's seat, a user with reduced physical ability manoeuvres the powerchair to the rear of the vehicle until it is adjacent to the lift and within line of sight of two highly reflective fiducials. On an input from the user (via a button press), a laser guidance system comprising of a compact Light Detection and Ranging (LiDAR) unit coupled with robotics fitted to powerchair, locates the exact position of the lift and proceeds to autonomously drive the powerchair onto the platform. In the event of the powerchair driving outside the autonomous control area, operation will cease instantly and user intervention through the joystick is required to return the chair to this area. As part of the development of ATRS, Freedom Sciences LLC conducted testing in varying environmental conditions to ensure that the system operated reliably. The tests included assessing the impact of different levels of rainfall on the fiducials, the effect of headlight interference on the LiDAR and outdoor public demonstrations where users with reduced physical ability conducted system-level tests (Gao et al. 2008). Overall, autonomous docking could be achieved in most environmental conditions, even in sand or dust extremes. There was an instance where the powerchair could not be autonomously docked when it entered a depression in the ground and could not gain sufficient traction to exit. However, this was not likely to occur in normal use of the system and was not a malfunction of ATRS.

ATRS represents a system that can provide an efficient alternative to a WAV (described in section 1.3) that maintains the safety of a standard vehicle as the rear crumple zones are not removed. However, the current system has a usability limitation in that the small wireless keyfobs (shown in Figure 10) (used to control the seat, lift and tailgate) have small buttons that are required to be held down in order to interact with the system and can also be dropped easily, which could be problematic for a powerchair user with reduced finger dexterity, especially if they fall out of reach (e.g. under the vehicle).

Figure 10: Wireless keyfobs

SmartATRS (described in section 6.2) was developed by Whittington et al. (2015) to provide the exact functionality of the keyfobs on a smartphone interface, which can be used as the case study for this research. SmartATRS can be integrated with additional interaction mediums to form a concept demonstrator. The 'off-the-shelf' interaction mediums to be considered for evaluation are described as follows.

2.8.3 Electroencephalogram (EEG)

The process of measuring electrical brain activity is known as electroencephalography and is performed by attaching electrodes to the scalp (Brain Products GmbH 2017a). The recorded electrical potential from neurons is transmitted as traces known as EEG. Electrodes are applied to the scalp using a conductive gel and are individually attached to a cap. The advantage of electroencephalography using a cap instead of a Magnetic Resonance Imaging (MRI) scan is that the process does not greatly restrict the participant's movements. Electroencephalography can also be performed invasively known as electrocorticography (ECoG) (Hill et al. 2012). The process involves placing electrodes below the scalp either above or underneath the dura mater. Compared to the signals obtained from EEG, the recorded electrical activity from ECoG has greater accuracy and is less susceptible to noise interference. Therefore, ECoG is used for neuroscience research, in particular monitoring the effects of epilepsy (Schalk and Leuthardt 2011). It can be concluded that ECoG would not be an appropriate method to monitor the brain activity of a user for this research.

Figure 11: Brain Products 64-Channel actiCAP (Brain Vision UK 2017)

The actiCAP developed by Brain Products GmbH (Brain Vision UK 2017) provides the method to non-invasively monitor electrical activity in the brain, as can be seen in Figure 11. The cap contains either 32 or 64 electrodes located at specific points on the scalp that can be connected prior to the user wearing the actiCAP (Brain Products GmbH 2017b). It is possible to disconnect or replace each electrode in the event of a malfunction. After the actiCAP is fitted to the user, it is connected to any EEG amplifier system that analyses the brain activity signal. Software developed by Brain Products GmbH called 'actiCAP ControlSoftware' runs on a computer connected to the amplifier to collect the data recorded. Analysis of the EEG can be performed using third party software such as EEGLAB.

By comparing EEG with ECoG, utilising an actiCAP is an appropriate method to provide interaction through the monitoring of brain activity due to being non-invasive. However, based on the review of the current status of EEG technology, it is apparent that there is an immediate disadvantage of being obtrusive compared to other modalities of interaction such as touch-based. As this aspect could be eliminated in the future with advances in technology, a feasibility trial is conducted with an actiCAP to determine which body movements result in detectable fluctuations in brain activity, which could be used as interaction triggers. Head tracking is investigated as an alternative to EEG, due to being non-obtrusive and considered as being suitable alternative interaction method for users with reduced finger dexterity.

2.8.4 Head-based Interaction

A form of a head-based interaction with smartphones is provided by Switch Control (Apple Inc. 2016), an accessibility feature for devices running the iOS operating system, i.e. an iPhone. The feature was introduced in iOS 7 and allows users with limited mobility to control the device with head movements, a series of ability switches or secondary assistive technologies. All gestures (e.g. pressing, dragging or pinching) recognised by iOS can either be performed with a head movement, pressing a connected secondary device or an alternative input method such as blinking.

Switch Control is enabled through the 'Accessibility' menu, under the 'PHYSICAL & MOTOR' tab and executed through creating a number of switches either from an external source (such as a third party button), an action on the screen or by the front facing camera. For head tracking, the camera is the only source that can be utilised to detect left and right head movements. A switch action is assigned to each movement and is selected from predefined actions.

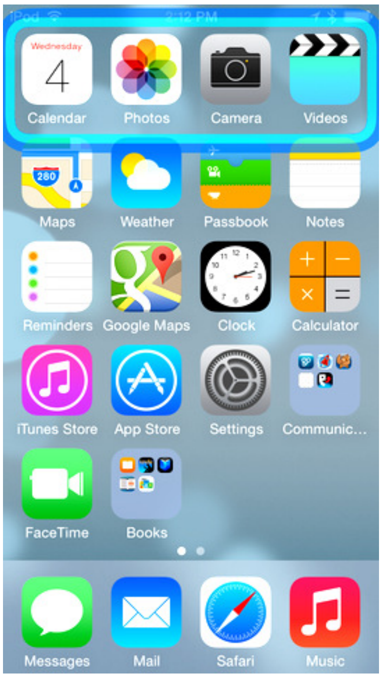

Figure 12: iOS Switch Control in Item Mode (Meza 2014)

The most suitable switch actions to facilitate head tracking are 'select item' and 'move to next item', which respectively executes the item (e.g. button) that is currently in focus and moves to the next item on the user interface. Switch Control can be used in two modes, Item Mode and Point Mode (Meza 2014). Item Mode can be used with an 'Auto Scanning' feature that highlights each item on the user interface (illustrated in Figure 12) and when the required item is highlighted, the user can select using the 'select item' switch action. To increase the navigation speed of Item Mode, the 'Group Items' setting is used to cluster similar items. For example, on the iOS

Home Screen, items are highlighted in rows and on selection of the desired row, Switch Control scans icon-by-icon. The scanning speed is user-configurable to assist novice users. When using Switch Control in Point Mode, any XY co-ordinate on the user interface can be selected using a single switch. Vertical and horizontal scanning bars are used to pinpoint an exact location, by firstly selecting the vertical position of the desired location and secondly specifying the horizontal position. The intersection between the vertical and horizontal scans is the location on the interface that will be selected. The scan speed is also user configurable, so slower scans could benefit new users of Item Mode. To improve the navigation efficiency the speed can be increased until an optimum balance between performance and accuracy is achieved.

There have been several examples where iOS Switch Control enables users who would otherwise not be able to interact with technology, to operate an iOS device by using switches attached to their powerchair. It has been stated that the ability to use interaction through switches is "a dream come true" for certain users (Hills 2014). The most popular mode of switch control is Item Mode, although there are examples of users who interact through Point Mode (Pretorian Technologies 2014). Point Mode is suitable for users who have necessary coordination to operate the switch at the correct time to produce a suitable intersection. It is possible to elicit guidance on using Switch Control via head movements (Buscemi 2013), but the application of this by users with reduced physical ability is less documented.

iOS Switch Control represents a feasible method to achieve non-obtrusive interaction using head movements. A significant advantage of this technology is that no additional hardware would need to be purchased, as Switch Control is a built in accessibility feature of the iOS operating system. There are a variety of operation modes that can be assessed to measure the usability and suitability for different physical conditions. Therefore, this technology could be incorporated into a framework, subject to results of a feasibility trial and subsequent user evaluation. In addition to head tracking, it is possible to track the face using facial features, which is investigated by determining whether Tracking-Learning-Detection (TLD) is a possible technology to implement on a smartphone.

2.8.5 Facial Feature Tracking

The real-time object tracking algorithm, Tracking-Learning-Detection (TLD 1.0), also known as the Predator tracker, was developed by Kalal et al. (2012) and has been released as open source software.

The purpose of TLD 1.0 is to track unknown objects in unconstrained video streams, such as movies and live streams from webcams. FaceTLD is a technique that builds on the TLD 1.0 algorithm to track a human face in videos where an offline trained detector locates faces and an online trained validator determines which face corresponds to the tracked subject. The system automatically tracks and learns the face from different angles. The advantage of FaceTLD is that it is robust to low frame rate video and does not confuse different faces. The outputs of TLD 1.0 are the positions of the tracked object in real-time to a text document.

Tracking-Learning-Detection 2.0 (TLD 2.0) is the next generation of the object tracking algorithm and was released 1.5 years after TLD

1.0. TLD 2.0 was developed by TLD Vision s.r.o[3]. Unlike TLD 1.0, TLD 2.0 has not been released as open source software and therefore a non-disclosure agreement is required between TLD Vision s.r.o and the discloser.

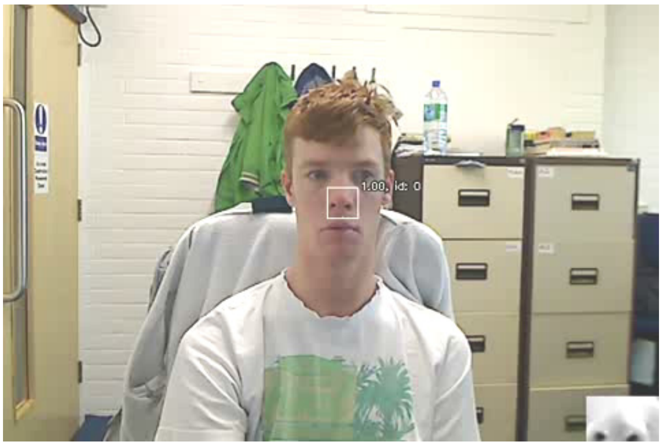

Figure 13: TLD tracking the nose

One application of TLD is to track a specific vehicle from an airborne or on-board camera. This could be useful for security purposes e.g. during a police incident where a car is tracked from a helicopter to assist personnel on the ground. The advantage of utilising TLD is that it would learn the shape and colour of the vehicle of interest and differentiate it from other vehicles on the road. As the algorithm learns in real-time, it would be anticipated that the accuracy of the vehicle tracking would improve as the pursuit of the vehicle progresses. A second application of TLD would be to track pedestrians on the ground from either an airborne or on-board camera to intercept perpetrators from a crowd of people, a challenge of typical long term tracking (Kalal et al. 2010).

Both TLD 1.0 and 2.0 are identified as technology that would provide user interaction via the face through a particular feature, e.g. the nose

[3] A research company established by Kalal.

as can be seen in Figure 13. However, it is suspected that TLD 2.0 provides increased performance based on being approximately eight times faster, able to track multiple targets and rotating objects and a C++ implementation (TLD Vision s.r.o 2015). TLD also has the advantage of being non-obtrusive. These characteristics can only be assessed through conduction of feasibility trials. If the algorithm is seen to perform as expected, it could be an alternative technology to incorporate into a framework that provides interaction through the face. It is anticipated that the suitability of the technology would rely on a smartphone implementation being developed that can be adaptable to suit the individual abilities of users. As an alternative modality, the head can also be utilised for Head Mounted Displays (also known as smartglasses), where interaction is provided through a user interface displayed on glasses. Existing 'off-the-shelf' smartglasses will be explored to assess whether a suitable interaction medium can be created for users with reduced physical ability.

2.8.6 Head Mounted Displays

Head Mounted Displays (HMDs) or smartglasses can be defined as "non-immersive devices capable of transmitting image data to the wearer, while still allowing the wearer to view their surroundings in real time" (Elder and Vakaloudis 2015). These devices can also be classified as wearable technologies defined as "compact devices that present information to users and enable user interaction, either through voice command or physical input" (Iqbal et al. 2016). Although, HMDs have widely been utilised in the military and healthcare domains (e.g. for emergency workers to receive hands-free information about the status of operations (Elder and

Vakaloudis 2015)) for a number of years, the technology has only recently been adopted by the commercial sector through smartglasses. In general, smartglasses do not provide increased input and output capabilities or processing power compared to smartphones, but have the advantage of minimising the time taken to perform tasks due to being wearable. As the battery is small due to the minimal space available the charge capacity is reduced compared to smartphones. A small display is projected in the user's peripheral vision, therefore enabling navigation in real world environments with minimal disruption. Other common features included are sensors in the form of cameras and microphones to record the environment, as well as a Global Positioning System (GPS) and accelerometers to interpret the environment by determining the user's position and orientation. It is common for smartglasses to have the facility of pairing with a smartphone via Bluetooth, so that users are able to receive notifications of calls, texts and emails without the need to directly view the device.

One of the original smartglass products was the Google Glass (Google Inc. 2016) that initially dominated the market in wearable technology. Subsequently, other developers such as Recon Instruments, Sony, Apple and Samsung have developed their own smartglass devices that can be used in domains from healthcare (Muensterer et al. 2014), plant science (Cortazar et al. 2015) and sports (Sörös et al. 2013). The Recon Jet shown in Figure 14 (Recon Instruments 2017a) is a type of smartglass specifically developed for cyclists to assist with navigation and record elements of their activity including distance, speed and duration. As an offset of the smartglass market, snow goggles (Recon Instruments 2017b) have evolved that are designed for winter sports and provide location tracking and barometric data to assist with navigation in the mountain environment.

Figure 14: Comparison of the Recon Jet (Fuller 2015) and MicroOptical (The VR Shop 2015) head mounted displays

There are numerous instances of HMD use in healthcare. The MicroOptical HMD (Ortega 2008) also illustrated in Figure 14 has been used in orthopaedic surgery to view fluoroscopy images instead of a standard monitor. The study concluded that the HMD reduced the amount of time the surgeon's focus was distracted from the patient, however, a limitation was presented in that the HMD could only view a single image. Also, the requirement to wear the HMD caused issues with imbalance for the surgeons. A similar application of a HMD was by the Opti-Vu High Definition Video Display to improve performance during laparoscopic tasks rather than using a standard monitor, where it was highlighted that 66% of younger participants preferred the HMD compared with only 20% of seniors (Maithel et al. 2005). This showed the possible difficulty of technology acceptance with the older generation. Smartglasses have also been applied to simulation-based training to create virtual environments, for example Wu et al. (2014) describe the application of Google Glass to train medical students where it was demonstrated that the HMD successfully trained the participants and was perceived to be comfortable to wear. There has been an example of a HMD used as an assistive technology; a Primesense 1080/Xtion (Figure 14) provided visual guidance for people with reduced visual abilities (Hicks et al. 2013) where surrounding objects are detected by the HMD with the distances relayed to the user via fluctuations in the brightness of the display.

Even though HMDs are considered as wearable, therefore obtrusive, technologies, the devices create fewer challenges compared to EEG. HMDs will not have a time consuming preparation stage and can be easily worn by the user, providing that they have sufficient finger dexterity to place the HMD on their head independently. The cost of the devices are also more reasonable than EEG as they are currently commercially available as products for the sports market. To further investigate the use of smartglasses as an assistive technology, the Recon Jet is considered to be viable as it is commercially-available, unlike the Google Glass that ceased production in January 2015 (Woolf 2015). This represents an alternative modality of interaction to include in a framework for people who do not have the required abilities to interact through standard touch or voice-based interfaces. Establishing a framework to recommend technologies to users that can be successfully exploited to the assistive technology domain requires consideration of industrial development processes and the implications to be addressed.

2.9 Industrial Development

The research will focus on the development of a framework and concept demonstrator that can be exploited to the user community of people with reduced physical ability and the assistive technology industry. The framework and demonstrator are viewed as SoS that can be related to a software development process. The Capability Maturity Model (CMM) for Software is a framework devised by the Software Engineering Institute (SEI) (Paulk et al. 1993) describing the important stages of an efficient software process. The publicly-available CMM was created by performing observations on existing software processes and non-software organisations.

The framework contains five maturity levels that are sub-divided into key process areas, which are further sub-divided into common features. Figure 15 shows the structure of the CMM.

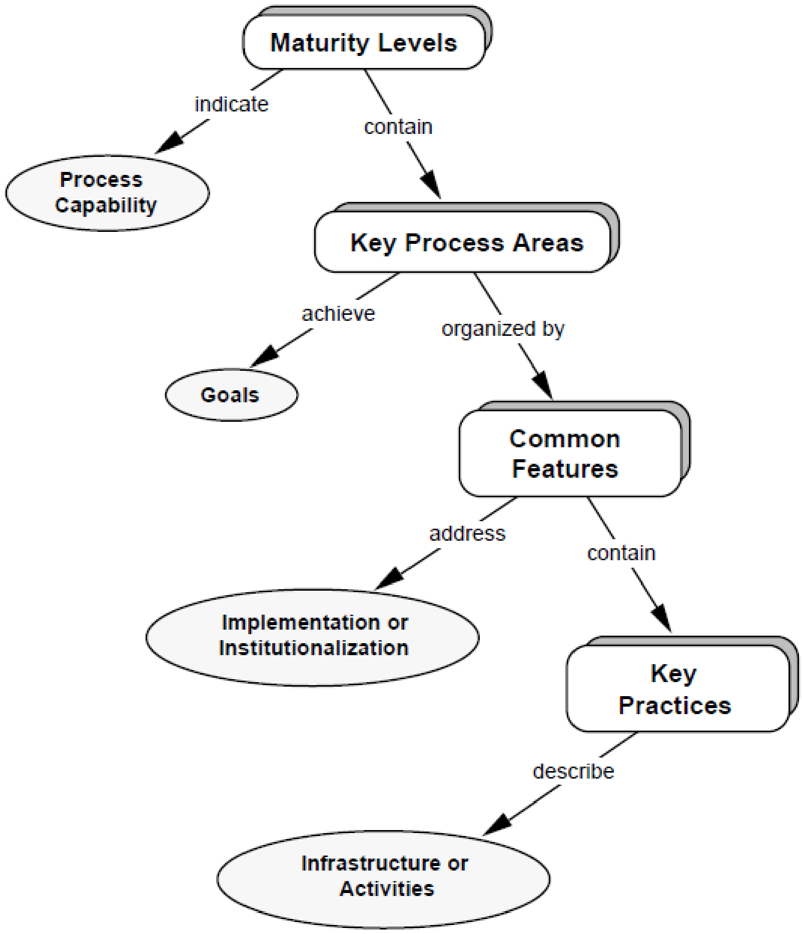

Figure 15: CMM structure (Paulk et al. 1993)

The maturity levels create the top-level structure of the CMM and are evolutionary plateaux, with each level containing a set of expected results, known as 'process capability'. This is used by organisations to predict the expected results from future software projects. The key process areas describe the related activities that contribute to the goal of maturity level. Each process area has an individual goal that determines the boundaries and scope. There are five Common Features attributes that describe implementation activities and institutionalisation factors; Commitment to Perform, Ability to Perform, Activities Performed, Measurement and Analysis, and Verifying Implementation. The Key Practices level characterises the activities to be performed for each key process area.

There are five levels of software process maturity stated in the model as illustrated in Figure 16.

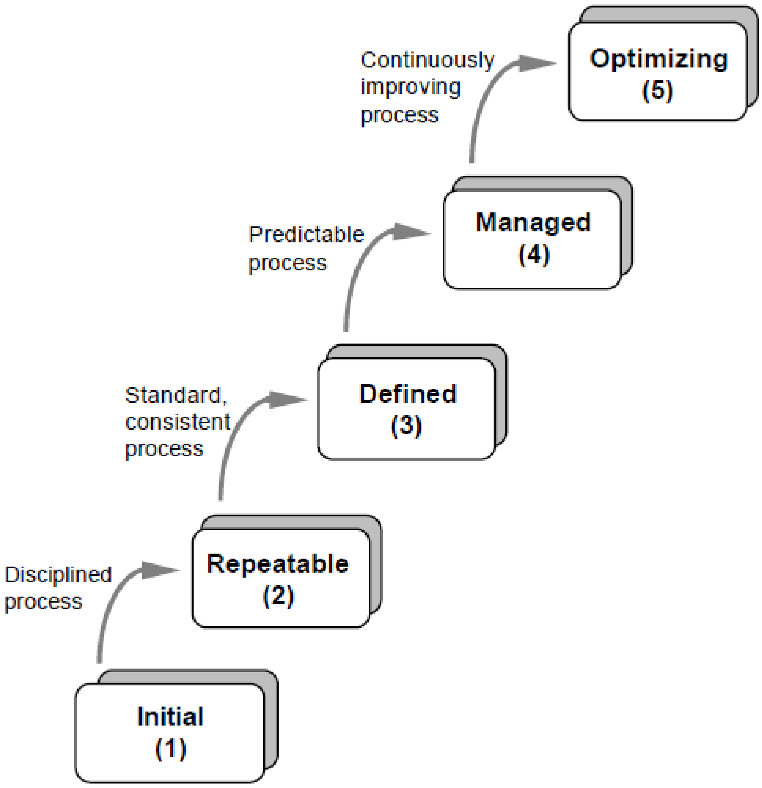

Figure 16: Levels of software process maturity (Paulk et al. 1993)

Organisations which are classified as being in Level 1 do not possess the necessary environment to develop and maintain software and there is a lack of management practices. The process is modified during the development and therefore, the resulting product quality can be unpredictable. Level 2 organisations have the necessary management practices in place to allow for disciplined, repeatable software processes where the costs, schedules and functionality are recorded. The presence of project standards ensures successful projects and a good customer-supplier relationship. Organisations characterised as Level 3 have well-defined, predictable processes for developing and maintaining software that are followed throughout the organisation. An organisation-wide training programme exists to ensure that all employees have sufficient knowledge. Quantitative quality goals are established in Level 4 organisations to measure productivity and quality, with the results stored in a software process database. The software processes in these organisations are predictable and deliver software products of a high quality. The optimum level is Level 5, where organisations are able to identify deficiencies in their processes and pro-actively identify their causes. The software process for Level 5 organisations is therefore, described as continuously improving. Cost-benefit analyses of new technologies are performed using data on the effectiveness of the software process.

The CMM was reviewed due to being a model used in industry to develop mature products. The framework can be considered as a software project and therefore the CMM is relevant. As the framework will need to be exploited to the domain in order to benefit the user community, the aspects of the CMM will need to be followed. The framework development will be performed by a Level 1 organisation that does not have a background in the domain. The purpose of developing the concept demonstrator will be to assess suitability of technologies for the intended user community. For the framework to be exploited, it will be provided to organisations classified as being at least Level 3. This will ensure that the framework is validated to maximise the chance of successful exploitation in the assistive technology domain.

2.10 Summary

The review of the literature focuses on the relevant aspects of reduced physical abilities and classification systems, the Equality Act

2010, ROM, HCI concepts of Ergonomics of human-system interaction concerning human-centred design and Design For All, multimodal interaction, SoS, assistive technologies and industrial development.

Existing classification schemes for reduced physical ability identifies that the International Classification of Functioning, Disability and Health Framework (ICF) is the most suitable to utilise, as it presents an improvement over previous schemes. The process of combining ICF with the Downton Scale and impairment types, performed by Andrews (2014), is an efficient technique to enhance the ICF. The physical conditions stated by Andrews (2014) established the causes and contraindications of each physical condition to produce a table describing the relationship between suitable input devices, which could be incorporated into a framework. Analysis of the Equality Act 2010 highlights the considerations that need to be addressed by a framework to ensure that suitable technologies recommended, conform to the legislation. ROM is a suitable method of characterising the user's ability in terms of the movements that are possible to perform without assistance from another individual and therefore, contributes to a Human aspect of a framework. To relate this aspect to technology, it is necessary to consider the HCI concepts of Human-centred Design for interactive systems and Design For All to maximise the potential of a framework to assist with users' daily lives. The multimodal interaction of the framework provides flexibility and reliability for the user and needs to be combined with a SoS and SoI-based approach. The characterisation and description of a framework SoS provides a holistic view and supports the development of a concept demonstrator. The technology aspects of a framework primarily contains assistive technologies, which could contain 'off-the-shelf' products. Solutions for transporting powerchairs as well as alternative interaction modalities including head-based interaction and smartglasses are considered to be relevant to a framework. To ensure successful exploitation of a framework to the assistive technology and healthcare domains, industrial development processes are necessary to be adopted.

Chapter 3 Research Methodology

This chapter describes the philosophical principals of methodology selection by identifying whether the research suits the Positivism or Interpretivism paradigm (Collis and Hussey 2013). The classification of approaches to research methodologies will be discussed, including action research, cross-sectional studies, ethnography, case studies, surveys and experimentations. Discussion of alternative research designs are provided along with the rationale behind the author's selection of research methodology.

3.1 Research Design

The research study framework established by Saunders et al. (2015) to describe a methodological study involving different methods of data collection can be illustrated by the research process 'onion' (Figure 17). The model contains five layers, identification of the Research Philosophy, Research Approaches, Research Strategies, Time Horizons and Data Collection Methods.

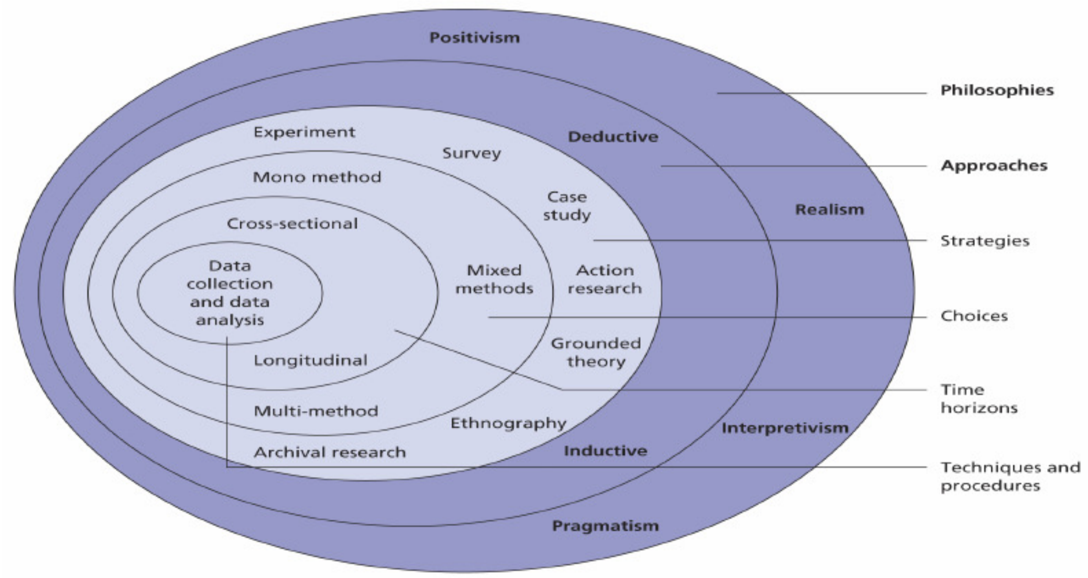

Figure 17: Research process 'onion' (Saunders et al. 2015)

This chapter will be structured around the research process 'onion', beginning with Research Philosophy and concluding with Data Collection Methods. The outer layer of Research Philosophy concerns the set of beliefs relating to the nature of the reality being investigated (Bryman 2012), for example Positivism or Interpretivism. The aims of the research determine the approach based on the starting point of the researcher and the types of data involved, i.e. qualitative or quantitative. The Research Strategy defines the intended process of performing research and the applicable strategies are discussed, including experiments, surveys, case studies, Action Research (Participative Enquiry). The Time Horizons layer states the time scale of the research project and therefore, determining whether a cross-sectional or longitudinal study is most suitable. The fifth layer contributes to the reliability and validity of the research as the data collection and analysis methods are dependent on the selected type of methodological approach.

3.2 Research Philosophies

It is recognised that the purpose of research includes: investigating existing situations or problems; providing solutions to problems or constructing and creating new procedures or systems (Collis and Hussey 2013, p. 2), all of which are applicable to this research. Philosophy can be defined as a system of beliefs that originate from the study of the fundamental nature of knowledge, reality and existence (Oxford Living Dictionaries 2016a). Collis and Hussey (2013) also describe two distinct philosophical frameworks (paradigms) to guide the conduction of scientific research; Positivism (formerly known as Positivistic) and Interpretivism (formerly Phenomenological). The characteristics of the two paradigms are described in Table 2.

Table 2: Positivism and Interpretivism paradigms (Collis and Hussey 2013)

Positivism Paradigm	Interpretivism Paradigm
Tends to produce quantitative data Uses large samples Concerned with hypothesis testing Data is highly specific and precise The location is artificial Reliability is high	Tends to produce qualitative data Uses small samples Concerned with generating theories Data is rich and subjective The location is natural Reliability is low

Validity is low Generalises from sample to population	Validity is high Generalises from one setting to another

Positivism research relates to quantitative analysis of numerical data, where independent conclusions can be formed by researchers through empirical research (through observations and experimentations) to discover theories (Collis and Hussey 2013, p. 343). However, the conclusions obtained from Interpretivism research are subjective and vary depending on the individuals performing the research. In contrast, Interpretivism research applies qualitative methods that seek to describe and translate the results (Collis and Hussey 2013, p.342).

This research is considered within both paradigms as it contains applied and deductive aspects (further described in section 3.3), hence this pragmatic approach is the most suitable for developing a framework. Therefore, a predominately Interpretivism approach is adopted with some characteristics from Positivism. An Interpretivism paradigm is adopted as the author interacts with the phenomena under study and the findings of the research are reliable through validations. A select sample was utilised in order to ascertain an in-depth understanding of participants' specific abilities and the usability of technologies.

3.3 Research Approaches

Collis and Hussey (2013) identified three research approaches: quantitative or qualitative, applied or basic, and deductive or inductive. Quantitative consists of examining numerical data compared with qualitative that analyses less tangible aspects of research. From the outset, applied research aims to apply the findings to a specific purpose whereas basic research improves knowledge generally but does not have a defined application. Deductive research starts from general theories and develops theories that are specific to a case study, whereas inductive research approaches research from the opposite direction, initially applying the research to a specific situation before developing general theories applicable to a range of case studies. Quantitative, Basic and Deductive research is associated with a Positivism paradigm, whereas Qualitative, Applied and Inductive research relates to an Interpretivism paradigm. A quantitative approach relates to the collection of quantitative data that is validated through statistics (Flick 2011), whereas in qualitative research, the process is determined by the participants rather than by the researcher, e.g. interviews where open questions are posed allowing the researcher to shape the interview as it progresses (Feilzer 2010).

A deductive approach is applicable to this research as it concerns the interaction between people with reduced physical ability and technology to assist in their daily lives. Furthermore, the researcher (author) had a clear motivation prior to commencing of improving Quality of Life specifically for people with similar reduced physical ability. This is subsequently tested through the involvement of the intended user community to create specific technology solutions. Quantitative analysis is necessary to provide a structured approach which evaluates the usability of technology and suitability for people with reduced physical ability.

3.4 Research Strategies and Methods

The research strategy defines the method in which the researcher will obtain results and can be performed through the adoption of approaches (Saunders et al. 2016, p.177) including experiments, surveys and case studies. The strategies to be implemented by this research are discussed.

3.4.1 Action Research (Participative Enquiry)

Action Research is when the researcher intervenes in a situation to analyse change before monitoring and evaluating results (Neville 2005). A key aspect of the strategy is the participation of a client to determine the objectives and the methods in which these can be met. The success of Action Research is the active co-operation between the researcher and the client as well as the ability to conduct adjustments to the methodology based on information obtained from the client. When the client consists of a group or organisation involved in the research, a strategy of Participative Enquiry is adopted, which follows the same principles as Action Research, but requires sharing, agreeing and co-operating within the group to ensure that the process is as equal as possible (Neville 2005). Action Research represents an additional strategy to produce theories for the

Interpretivisim research. The research is viewed as Participative Enquiry concerning a user group of people with reduced physical ability where technologies are evaluated to determine the contents of a framework.

3.4.2 Case Studies

Case studies are in-depth analyses of a particular subject and are performed through the gathering and analysing of information that can be utilised to establish theories. Case studies can either be Descriptive, Illustrative, Experimental or Explanatory (Scapens 1990). Descriptive case studies can be applied to the research through describing current assistive technologies and Experimental case studies can examine the difficulties with new technologies being adopted by people with reduced physical ability. Performing case studies enables theories to be generated for the Interpretivisim research.

3.4.3 Experiments (Experimental Studies)

Experiments (also known as experimental studies) can be performed in a controlled and structured environment to identify and analyse the causal relationships between phenomena (Neville 2005). These studies can either be performed in a controlled laboratory environment or in a real-world environment known as Field Studies. Within either environment, the variables can be controlled or modified to observe the effects of the experiment subjects. The key difference between these two types of experiment are that in a controlled environment, the artificial aspects can affect the outcome from the participants, however, in the real-world environment, there is less control on external variables. Experiments conducted as Field Studies are more suitable to the research domain to provide a realistic environment to assess technology usability, thus adhering to the Interpretivisim paradigm.

3.4.4 Focus Groups

Focus Groups are a form of group-interviewing that can be defined as 'a group of individuals selected and assembled by researchers to discuss and comment on, from personal experience, the topic that is the subject of the research' (Powell et al. 1996) in the form of an organised discussion. The discussion aims to obtain the participants' attitudes, beliefs, feelings and reactions that would not otherwise be possible to elicit from alternative methods such as individual interviews. The key aspects to a successful group is interaction between the participants, so that a rich understanding of the collective views and rationales can be generated (Gill et al. 2008). If the participants are uncomfortable with each other, it is likely that their opinions will not be portrayed during the focus group. Stewart and Shamdasani (2014) recognise that group size is important and recommend that a greater number of participants is advantageous to having an informative discussion compared to an under-recruited group that may cause the session to be cancelled. It is suggested that the optimum size for a focus group is between six and eight participants, as an over-recruited group can result in disorganisation and unequal opportunities for participant contribution (Bloor et al. 2000).

3.4.5 Interviews

Interviews provides opportunities to explore the views, experiences, beliefs and/or motivations of individuals regarding specific matters (Gill et al. 2008) and can be either structured, semi-structured or unstructured. Structured interviews contain verbally administered questionnaires with no scope for elaboration through follow-up questions, whereas as unstructured interviews do not have pre-determined questions that can lead to the interview being time-consuming and challenging to manage. Semi-structured interviews present a balance between the two methods whereby key questions are provided to define the areas for the interviewing to discuss and offer opportunities for elaboration (Britten 2006). It is advised that interviews are conducted when limited information is known about a study phenomena and detailed insights need to be elicited from the individual participants (Gill et al. 2008).

Surveys are conducted by selecting a representative and unbiased sample of subjects for the intended user community and can either be performed as face-to-face or as telephone interviews using questionnaires, or both methods. There are two types of survey, a descriptive survey to identify and ascertain the frequency of a particular response from a user community, or an analytical survey to establish the relationships between variables within a user group (Neville 2005). The sample size represents the number of respondents selected from the overall population and is an important consideration in surveys, as it will define the reliability of the results in a quantitative study. Generally, the larger the sample, the greater the reliability of the results (Marley 2016). However, as the research is Interpretivisim with small samples of data, face-to-face interviews are more suitable to provide rich data from the participants.

Through a combination of strategies consisting of Field Studies, Descriptive surveys, Descriptive and Experimental case studies and Action Research, a framework is established that is suitable to the assistive technology and healthcare domains. Each strategy has benefits to the framework development and enabling rich and robust data to be obtained from the user community. The selected strategies complement one another to present a fuller picture of the phenomena under study.

3.5 Research Time Frames

The time framework (also known as the Time Horizon) for research refers to the project completion time (Saunders et al. 2016, p. 200). Different time frames are summarised in Figure 18 by Kumar (2014).

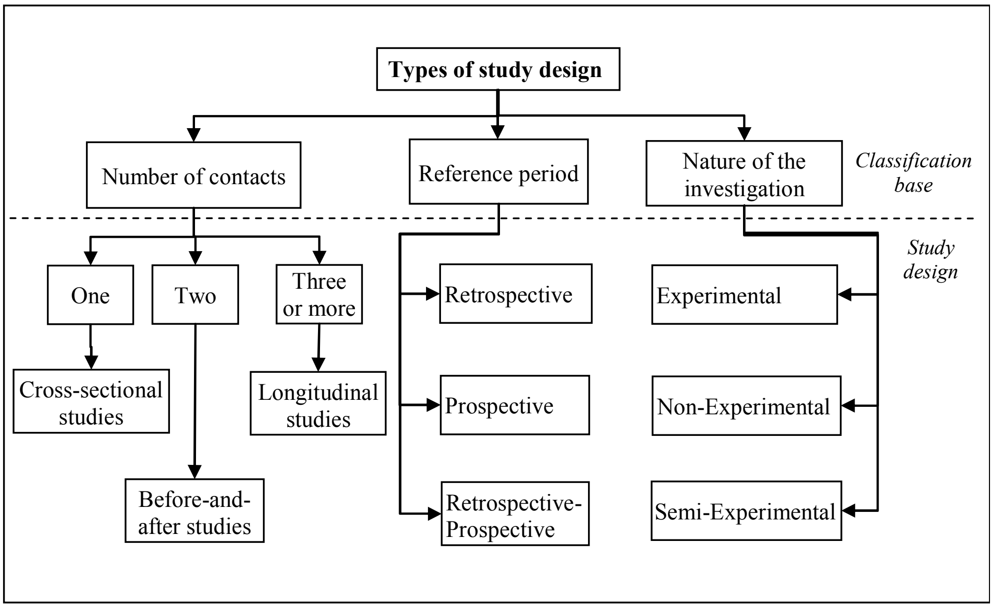

Figure 18: Types of study design (Kumar 2014)

Cross-sectional studies are often used in research that measures the trends in a particular phenomenon by taking cross-sections of a population at a particular point in time (Flick 2011). Longitudinal (or Before-and-After) studies are repeated cross-sectional studies over a period of time. Each study is from an identical population, but may not be with the same respondents. The intervals between each study can be of any length, from a week or over a year. The aim of longitudinal studies is to examine change over time (Goddard and Melville 2004). Longitudinal studies have the disadvantage of a panel conditioning effect (Halpern-Manners and Warren 2012). This occurs if the same respondents are approached frequently and may respond differently as they are aware of the expectations of them.

The reference period defines the timeframe in which the phenomenon is being studied. Retrospective studies only research phenomena that occur in the past, whereas prospective studies seek to determine the future outcome of the research. Retrospective-prospective is a combination of both approaches and therefore studies on past trends and future outcomes of a phenomenon (Kumar 2014). In this research design, data is firstly collected prior to the research being performed and again after research has been conducted. The nature of the research investigation can either be experimental or non-experimental. Experimental studies involve introducing intervention and observing the effects, whereas non-experimental studies observe the effects in order to determine the cause (Kumar 2014).

The author has selected a cross-sectional study research time frame as the current difficulties that people experience in their daily lives are analysed at a particular time (i.e. during requirements elicitation). Similarly, usability evaluations of technology are conducted at a specific phase in the research and not repeated over a period of time to examine changes. As the time available for this research is limited, cross-sectional studies are also more suitable as a 'snapshot' in time is obtained (Neville 2005). However, the usability evaluations could be seen as individual Before-and-After studies to determine the effect on technology integration. The research is best suited to a prospective approach as it aims to develop a framework that can be used in the future to recommend technologies that have been shown to improve usability through evaluations involving the user community. It is an entirely experimental study that introduces technology into the lives of people with reduced physical ability and observes the effect on their ability to perform tasks.

3.6 Research Methods Adopted

A research method is defined by Neville (2005) as the ways in which data can be collected and analysed, e.g. through questionnaires and interviews. A quantitative approach is adopted to collect and analyse numerical data (e.g. controlled usability evaluations). The adopted methods are described below.

3.6.1 Literature Review

The four key objectives of a literature review are to survey literature in the domain of study, synthesise a summary based on information contained within the literature, critically analyse the information by identifying theories and limitations, and present the literature in an organised format (Royal Literary Fund 2016). The state-of-the-art literature review for this research analyses the domains of physical conditions, HCI, SoS, assistive technologies and industrial development to identify the methods that could be adopted by research. The review describes the approaches that were selected for implementation during the development of a framework.

It is necessary to conduct a literature review to ascertain the current state-of-the-art regarding the relevant domains to the research prior to the development of a framework. A review into the types of physical conditions that exist enables an understanding to be obtained about the potential users of technologies and the physical challenges that they may encounter. The HCI element of the literature review informs the principles and guidelines that would need to be followed in order for a framework to be implemented that has maximum potential to assist the user community. Due to the framework and the incorporated technologies being considered as constituent systems, the SoS domain is relevant to be reviewed. The review of currently-available assistive technologies forms the basis of the technology aspect of a framework. The final industrial development section of the review provides the procedures that will need to be followed to achieve exploitation of a framework. A literature review allows the views from other experts in the domain to be elicited and built upon during the research.

3.6.2 Design Approaches

Requirements Analysis (also known as requirements engineering) involves the discovering, developing, tracing and analysing requirements that define a system (Hull et al. 2011). A requirement is a statement that identifies the functional or design characteristics of a product, which is unambiguous, testable or measureable (Hull et al. 2011). Requirements that meet these criteria are known as 'Atomic Requirements', as they provide enough detail without the need for further breakdown (Robertson & Robertson 2009). To define Atomic Requirements, the Volere Requirements Shell (also known as a Snow Card) can be used to identify the necessary attributes including Description, Rationale and Fit Criterion. 'Volere' originates from the Italian verb (to wish or to want), and is a requirements technique that is used by thousands of organisations worldwide (Atlantic Systems Guild 2017). The shell identifies a number of attributes that form one atomic requirement and can be adapted to suit the project's objectives and are commonly used for software engineering, e.g. Sharp et al. (2015) during the development of a mobile learning system. By using this template as a guide to writing requirements, it can be ensured that each requirement is complete. Requirements can be prioritised using the MoSCoW technique originally developed by Clegg and Barker (1994), where the categories of 'Must', 'Should', 'Could' and 'Won't'/'Would' determine whether the requirement has to be met by the solution. The requirements for the research are elicited by investigating the difficulties to be solved through the application of technology. It is necessary to conduct prior to commencing the development of a framework to enable the difficulties that are currently encountered by the user community to be elicited in order to ensure that the framework would be suitable for the domain. Using the MoSCoW technique to prioritise requirements allows the characteristics that will need to be measured in the feasibility trials and evaluations to be ordered in importance.

Questionnaires establish the difficulties experienced and the participants' interest in technology by providing description of off-the-shelf technologies. The questionnaires are disseminated through online tools to maximise the number of potential respondents. Questionnaires were deemed to be appropriate as they enabled a large number of respondents to be contacted without the need to arrange visits. The format of a questionnaire enables the respondents to portray their views through closed-ended questions (e.g. requiring a yes/no response) that are less time consuming to complete, as well as open-ended questions (e.g. one word answers) that allow greater description to be provided.

Semi-structured interviews are devised based on the questionnaires and conducted at a special educational needs school and a residential home for people with reduced physical abilities. It is necessary to conduct semi-structured interviews as an alternative for participants who are not able to conduct questionnaires due to their reduced physical ability. Secondly, some participants may prefer an interview as it may be easier to communicate orally rather than through written means. The interviews also have a benefit of having a captive audience to compensate for a potential low response rate to the questionnaires.

Manufacturer requirements are elicited from Dynamic Controls through a meeting performed over Skype. The combined user and industrial partner requirements are defined as Atomic Requirements in Volere Requirements Shells. Implementing the Volere technique allows the requirements to be structured with fit criterions that demonstrate how the requirements can be tested for satisfaction.

Case studies are a strategy to provide an in-depth analysis, as described in section 3.4. This strategy is commonly applied to technology research as a basis for studies, for example, how web technologies are utilised in higher education (Bennett et al. 2012) and the social perceptions of interacting with a wearable technology in a public environment (Profita et al. 2013). In this research, the case study analyses SmartATRS as real-world applications of assistive technology. As SmartATRS will be used as the research case study, it is essential that a full understanding of the system architecture and functionality is obtained so that additional technologies could be integrated into the system for the feasibility trials. This will result in controlled usability evaluations with technology that are safely incorporated into the system without any adverse effects on the operation.

Hierarchical Task Analysis (HTA) is a technique that was originally developed for the chemical processing and power generation industries (Annett 2003), but can be applied to any domain to provide a structured, objective approach to understand the tasks that users need to be perform in order to achieve their goals (Hornsby 2010). HTA can be adopted to assist with the design of a new system to investigate the potential approaches to complete a certain task, but can also be applied to analyse user experience by comparing different approaches to the performance of an identical task. The aviation industry provides examples of utilising HTA where the technique has been used to define the tasks involved with an autoland system (Marshall et al. 2003), however, it can also be applied to describe routine tasks such as boiling a kettle (Stanton et al. 2013). HTA as a user experience analysis technique is applied to define the structures of the controlled usability evaluations through the identification of the components of the case study. It is necessary to have a defined structure for evaluations so that they can accurately assess the usability of the technologies when applied to an existing assistive technology. Deriving tasks based on the HTA ensures that all elements of SmartATRS can be tested by the participants of the evaluations to provide an accurate assessment of the technologies.

Simulations: By definition, a simulation is a 'imitation of a situational process' (Oxford Living Dictionaries 2016b), which can be applied to research as an investigative method to provide results that could otherwise not be obtained due to feasibility, safety, ethical or time–based restriction (Cheng et al. 2014). A common application of simulations is in aviation, where simulators can either be used for pilot training (e.g. Virtual Aviation 2016), or for leisure activities through software flight simulators (e.g. Microsoft Corporation 2011). Simulations can also be applied to the healthcare domain to represent challenging patient situations including cardiac arrest and seizures (Cheng et al. 2014). For this research, a simulation is employed in two of the controlled usability evaluations to eliminate the use of a vehicle and the ATRS components while ensuring the safety of the participants in an indoor environment. It is necessary to conduct the evaluations with an ATRS simulation due to the author's requirements to use the assistive on a daily basis for independence. Secondly, due to the physical nature of ATRS, there are potential risks created by unfamiliar users operating the system, both to themselves (due to being in an outdoor environment) and to the vehicle (e.g. closing the tailgate whilst the lift is not stowed). Therefore, the development of a simulation that creates an accurate representation of the real-world scenario by displaying video clips illustrating the functioning of ATRS seemed appropriate.

3.6.3 Usability Evaluation

Usability defines the quality of a user's experience when interacting with products or systems, in terms of effectiveness, efficiency and satisfaction (Usability.gov 2016). A variety of factors contribute to usability including ease of learning, memorability, error frequency and intuitive design. The process of testing or evaluating usability can be performed by a variety of methods including focus groups, scenarios, surveys and interviews (Usability.gov 2016) and be a type of Participative Enquiry (defined in Section 3.4). The participants in the usability evaluations for this research involve people with reduced physical ability at the Victoria Education Centre, Talbot Manor residential home and visitors at the 2016 Mobility Roadshow. Usability evaluations can be controlled where certain factors are kept constant to illustrate statistical differences between conditions (Shneiderman and Plaisant 2014, p. 137), e.g. an evaluation to determine the usability of a 3D touch screen kiosk (Tüzün et al. 2016).

Controlled Usability Evaluations can be performed to compare the interaction mediums of keyfobs, touch-based, joystick and head tracking through the application of each technology to the case study. As the evaluations are controlled, cross-comparisons of the usability of the technologies can be made. The controlled aspect of the evaluations is to ensure that an identical series of tasks are conducted by the participants with each technology. As the feasibility trials are conducted individually by the author as hypothesis testing, the evaluations are necessary to be performed as applied experimentations to identify whether the technologies can provide assistance to the user community.

To evaluate usability, a number of methods are conducted.

Cognitive Walkthroughs are an evaluation method to understand the learnability of a system to new or infrequent users where a series of tasks and questions are conducted from the users' perspective (Usability BoK 2010). The technique was originally developed to evaluate public facilities such as Automated Teller Machines (ATMs) and interactive exhibits and can now be applied to more complex systems such as software development tools. Cognitive Walkthroughs have been applied to evaluate smartphone messaging applications (Jadhav et al. 2013), were established to define the process for each task and are usually conducted by usability experts. However, the Cognitive Walkthroughs conducted in this research were performed by the participants of the controlled usability evaluations to ensure that the evaluations were performed efficiently, reducing the time required due to the participants not needing to learn the process. The instructions avoided the use of technical language in order to be accessible to the user community. This technique is appropriate to ensure that the controlled usability evaluations are conducted safely due to the participants having a clear understanding of the tasks to be performed.

System Usability Scale (SUS) was originally developed by Brooke (1986) provides a "quick and dirty" reliable tool for measuring usability and contains a 10-item questionnaire with five response options from 'Strongly Agree' to 'Strongly Disagree'. An advantage of SUS is that the tool is inexpensive due to being non-proprietary and does not require a licence to be purchased. The tool is simple to implement due to having 10 prewritten questions that only has to be adapted to suit the application. The simple structure of the SUS questionnaire allows the participants to complete with a minimum amount of effort and comprehension required. A final advantage of the tool is that a single usability score can be obtained that provides efficient measuring of usability. SUS was the first technique used to compare interaction modalities by rating usability based on responses to a questionnaire. The responses were analysed using the Adjective Rating Scale (Bangor et al. 2009) to define the level of usability of each modality from 'Worst Imaginable' to 'Best Imaginable'.

NASA Task Load Index (TLX) is a subjective workload assessment tool that derives an overall score based on the subscales of Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. The tool has been utilised in a variety of environments from aircraft cockpits to laboratory testing (NASA 2017). NASA TLX is applied in the research to analyse the results of the controlled usability evaluations to measure the workload experienced by participants in terms of the subscales. The technique can determine the effect of each interaction modality on the user. Similar to SUS, the tool has the advantage of being freely available and has a generic structure that can be applied to any form of usability evaluation. The subscales of NASA TLX are highly relevant to the assistive technology domain as these are attributes that determine whether a technology will be appropriate.

The author considered adopting other usability evaluation techniques including heuristic evaluations to review interfaces by comparing the design against usability principles such as Nielsen's Heuristics (Nielsen 1995) and Think Aloud Testing where users are observed and asked to think out loud whilst interacting with a system (Usability BoK 2010). Heuristic evaluation was deemed to be unsuitable as it relies on the involvement of trained usability experts to apply the heuristics effectively. Think Aloud was also considered to be inappropriate as the users could find speaking affects performance adversely and could be difficult for users with reduced speech ability. Instead of NASA TLX, the Subjective Workload Dominance Technique (SWORD) could have been implemented to measure the workload experienced. SWORD is not as widely used as NASA TLX (Stanton et al. 2013, p. 315) with the main difference being that SWORD rates the workload dominance of one task against another. Therefore, SWORD only provides a rating for which tasks create greater workload than others and not a rating of the participant's workload. This would not have been suitable for evaluating technologies, as the differences between the interaction methods needed to be measured rather than the differences in domination between the tasks (Salmon et al. 2004). As an alternative to SUS, the Questionnaire for User Interaction Satisfaction (QUIS) (Human-Computer Interaction Lab 2016) could have been used, where participants rate 27 questions on a ten-point scale based on their satisfaction with specific sections of the user interface. QUIS was deemed relatively complex and had the risk of being more tedious for the participants to complete than SUS.

3.6.4 Quality Function Deployment (QFD)

QFD is a quality tool that was first developed by Mizuno and Akao in the 1960s, as a method for capturing the 'voice of customer' in order to build a product that considers customer satisfaction prior to the development (Akao 1990). QFD consists of four phases: product planning (known as the House of Quality (HoQ) matrix), product design to convert technical requirements into characteristics or systems, process planning that highlights the main process operations required to create the characteristics and production planning to determine the maintenance, training and control plans for operation. One example of a QFD application is to identify the customer needs for the public services within a smart city (Zawati and Dweiri 2016). QFD enabled scores to be calculated for each technical requirement that was used to prioritise. The highest priorities for the successful development of smart cities appeared to be smart services through websites and applications, the quality of smart services and collaborations with governments. The product planning phase of QFD is the most relevant to describing a framework as the included HoQ matrix can be adapted to suit the structure. The existing six sections of the HoQ are Customer Requirements, Planning Matrix, Technical Requirements, Inter-relationships, Roof and Targets, as shown in Figure 19.

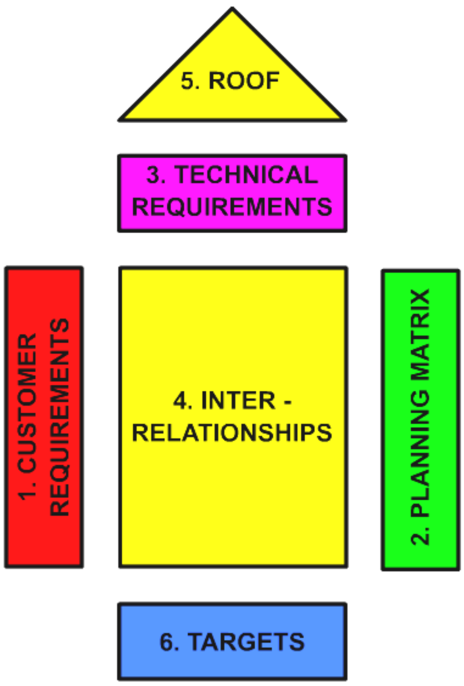

Figure 19: House of Quality matrix (Lowe 2000)

Customer Requirements contain a structured list of the product's customer requirements to describe their needs and difficulties, the Planning Matrix determines the requirement priorities, Technical Requirements determine the measurable engineering characteristics of the product, the Inter-relationships is a two dimensional matrix that translates the requirements expressed by a customer into technical product characteristics, the Roof matrix identifies the technical requirements that support or impede one another, and the Targets summarise the data contained within the entire HoQ in terms of technical priority, competitive benchmarks and targets (Lowe 2000). Due to QFD consisting of six elements that are connected by relationships, it is relevant to be applied to a framework that also comprises of different interrelated aspects. Illustrating a framework through this tool would allow a holistic view to be provided that will assist with the comprehension of the structure through visual means that describe the mappings.

3.6.5 Validation

It is recognised that research should be validated to ensure the integrity of all techniques and procedures to establish confidence in the outcomes for the intended user community (SWGFAST 2001). It is also important that the validation outputs are documented sufficiently in notes, reports or books so that the research can be replicated and is therefore reliable. Literature research (where relevant publications are assessed) are a form of internal validation that can be conducted prior to implementation of a new technique or procedure. External validation can occur once the research output has been completed and should involve a scientific, scholastic or professional organisation which is independent to the researcher and can be identified in documentation (SWGFAST 2001). This type of validation can take the form of a focus group where a moderated discussion is held to obtain the user's attitude towards a concept that often involve usability experts and stakeholders of the system, thereby becoming a form of Participative Enquiry (Section 3.4). The key aspect of a focus group is that participants discuss their experiences and expectations so that conclusions can be drawn (Usability.gov 2017). It is advisable that a moderator facilitates the discussion and the focus group is no longer than two hours in duration. A technique that can be used within a focus group are scenarios, where user groups are defined by personas explaining their context and can either be Task-based, Elaborated or Full-Scale. While task-based provides basic information only, Elaborated Scenarios offer greater detail regarding the users' characteristics and Full-Scale scenarios state the specific steps the user takes to complete the task. Validation with external individuals can also be conducted through surveys as described in section 3.4. Research involved technology is often validated through laboratory tests involving participants, for example, the Emotiv Epoc EEG gaming system was validated through the involvement of participants to determine that auditory event-related potentials could be reliably detected by a gaming device (Badcock et al. 2015).

A three-phase validation technique is implemented in this research to validate a framework to ensure suitability for the user community of people with reduced physical ability. The first phase (using Version 1.0 of the framework) involves conducting semi-structured interviews with visitors and assistive technology manufacturers at the 2016 Mobility Roadshow. The responses obtained are utilised to enhance the framework and establish Version 2.0. The second version is validated through a focus group of domain experts from computing and healthcare. The domain experts conduct the validation by applying Elaborated Scenarios based on the physical conditions of the participants from the roadshow to the framework. Following further enhancements to the framework, the final validation consists of semi-structured interviews with additional domain experts to assess the technology and healthcare aspects of the framework. It is essential to validate the framework to ensure that it addresses the aim and objectives of the research. The feedback that can be obtained from the user community and domain experts will ensure that the framework is appropriate and meaningful, thereby having maximum potential to provide improved quality of life to people with reduced physical ability. Table 3 provides a summary of the data collection methods adopted in this research.

Table 3: Adopted methods summary

Primary Aim	
To develop a framework to enhance multimodal interaction for people with reduced physical ability	
Objectives	**Methods**
1. To investiage the state-of-the-art that contributes to the assistive technology domain.	Literature review Internal validation
2. To elicit user and stakeholder requirements for a concept demonstrator.	Semi-structured interviews Questionnaires Manufacturer meeting Volere Requirement Shells
3. To conduct feasability trials and controlled usability evaluations of assistive technologies.	Participative Enquiry Descriptive case study Experimental case study Hierarchical Task Analysis Field Studies Controlled usability evaluations Simulation Cognitive Walkthrough NASA TLX System Usability Scale
4. To develop and validate a framework.	External Validations Participative Enquiry Focus groups Elaborated Scenarios Semi-structured interviews Quality Function Deployment

5. To disseminate a framework and set of guidelines for the assistive technology domain.	Conference papers Journal articles Presentations Application Development Exploitation Focus Groups

3.7 Summary

Research is a methodological study that consists of five layers from the outer layer of philosophy to the inner layer concerning the data collection methods to define the adopted approaches, strategies and time constraints. The two main research philosophies are Positivism that produces quantitative results and Interpretivism involving qualitative analysis. This research mainly adheres to Interpretivism principles, although a deductive Positivism approach is also undertaken. To obtain results, a variety of research strategies are employed including field study experiments of technologies in a real world environment, Descriptive requirement elicitation surveys, controlled usability evaluations and validations and application to Descriptive and Experimental case studies. Due to the time constraint, a cross-sectional study is most appropriate that assesses usability of technology at a particular 'snapshot' in time. The data for the research is collected through a number of suitable adopted methods from literature review, requirements analysis, usability evaluation and framework validation. Through the adoption of this research methodology, results can be obtained that satisfy the aim and objectives, which can subsequently be disseminated to the assistive technology domain.

Chapter 4 Research Results (i) – Requirements Analysis

4.1 Introduction

To establish the difficulties encountered by people with reduced physical ability in their daily lives and the technologies to investigate through feasibility trials, requirements analysis was conducted through surveys, interviews and collaborations with an industrial partner. The results are presented including defined Volere requirements for technologies to be incorporated into a framework.

4.2 Requirements Elicitation Method

Requirements were elicited through a survey containing questions regarding the respondent's challenges in daily life and the technologies that would be perceived to enhance their Quality of Life. The survey was provided to the respondent's either on-line, paper-based or as a semi-structured interview, with all formats comprising of the same question set.

A user group of people with reduced physical abilities was established through contacting the organisations listed in Table 21

(Appendix B) and used to distribute an online survey created through the 'QuickSurveys' website (Toluna 2017) (provided in Appendix C). Local organisations were identified for the semi-structured interviews who were responsible for people over 16 years of age with reduced physical ability. Visits were arranged to Victoria Education Centre (Livability 2017), a specialist school in Poole for students with physical disabilities.

Figure 20: Victoria Education Centre, Poole

Prior to the initial visit, authorisation was obtained from the Head of Post-16, who selected the students that were deemed the most suitable for the survey. A classroom was setup as an interview room and individual interviews were conducted with each student to ensure that their views were not biased. Each student was given an information sheet containing details about the reasons for conducting the interviews and on agreeing to participate, a consent form was signed either by the individual or their assistant. It was anticipated that each interview would take one hour, but in reality, only 30 minutes was required. All students had varying degrees of reduced physical ability, some of which affected their communication. Therefore, to ensure that the correct answers were recorded, the students were asked to clarify if necessary.

Initially, the survey posed questions regarding the users' background (e.g. gender, age and employment) before questions were posed about their reduced physical ability (disability). These questions ascertained whether their finger dexterity, speech or vision was impaired in order to identify any trends between physical conditions and technology requirements. Details on manufacturer and model of their powerchair and smartphone were obtained, as well as whether these were easy to use.

The main section of the survey identified tasks that the users found challenging performing inside and outside their homes. Each question contained a series of example tasks, such as opening and closing doors and operating appliances. These sets of tasks, doors and appliances were established through the author's personal experience of the challenges of having reduced physical ability and were supplemented with literature sources (e.g. appliances sold by online retailers). There was also an opportunity for users to add any alternative tasks that were not already listed. The users were asked to rate each list of tasks in terms of difficulty, with '1' being the most difficult.

As the technologies could be used in an outdoor environment under various forms of weather conditions, the survey contained questions regarding the conditions that users currently had difficulty operating their powerchair, such as in rain or at night. The users provided a description of why these conditions were challenging. For users who were able to drive a vehicle, questions were also asked about the challenges of operating any vehicle adaptations and secondary controls such as windscreen wipers. The final section of the survey listed pervasive technologies that could be incorporated into a framework. As the users did not have technology domain knowledge, a simple description was provided. Each technology was rated in terms of the interest to the users and a description of one task which the technology would benefit. The survey concluded with an opportunity for additional requirements to be stated and whether the users would like to be involved with future experiments with technology.

Through targeting the user group with a variety of survey formats, user requirements were elicited to contribute to the development of a conceptual model for a framework (described in Chapter 8).

4.3 User Requirements

The survey responses are presented in the following subsections and graphs are described fully in the Whittington et al. (2015b and 2015c) conference papers (referenced in Appendix D).

It was necessary to approach 32 UK organisations to establish a niche user group for the requirements elicitation survey in order to identify suitable participants between the ages of 12 and 70. Nine organisations were considered to be suitable (see Appendix B) while the remainder were not. The 16 selected participants were a mixture of genders from a variety of backgrounds (including students and the retired) who also had varying physical conditions (such as Cerebral Palsy, Arachnoiditis and Hydrocephalus, and Spinal Muscular Atrophy) with either dexterity and/or speech impairments. The participants thereby became a representative sample to accurately elicit the user requirements. Seven participants completed the online survey and the remainder were interviewed.

A transcript of the comments from the survey questions are provided by Tables 23 to 27 in Appendix E. The following pie charts provide an illustration of the proportion of the sample that encountered challenges with various activities.

Tasks inside the home: Figure 21 shows that 58% of participants found the most challenging to be opening/closing curtains and windows. The comments noted that causes of these challenges were due to the curtains/windows either being out of reach, inaccessible (due to obstacles such as furniture) or requiring a significant level of physical activity to be exerted.

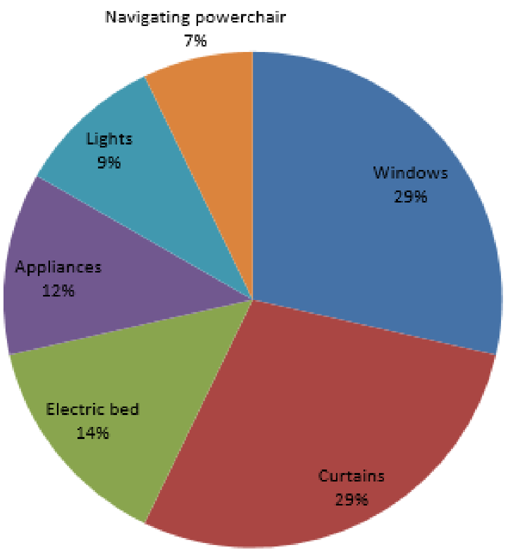

Figure 21: Challenging tasks inside the home

Doors in the home: It is illustrated in Figure 22 that 27% of users identified front, back and patio doors to be the most challenging to open and close, followed by garage doors. A comment was that doors required concentration to simultaneously drive the powerchair and open/close the door. Users with reduced finger dexterity found that door handle position, the weight of the door and locks to be issues. Others commented that they could only manage doors if they were left unlocked.

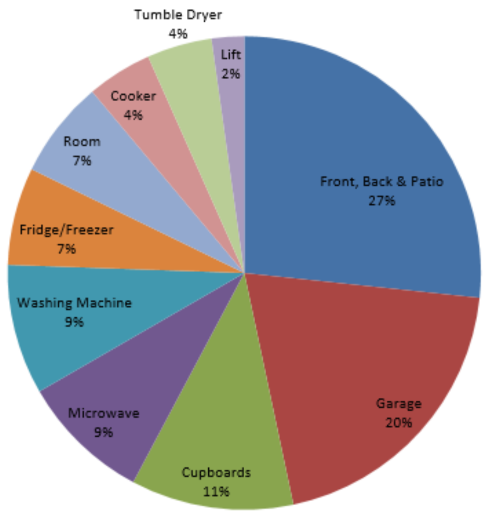

Figure 22: Challenging doors in the home

Household Appliances: Cookers and heating controls were identified as the most challenging to operate by 38% of users (Figure 23) who commented that cookers become hot and heating controls have small dials. Microwaves and kettles were the next most challenging with 25% of users.

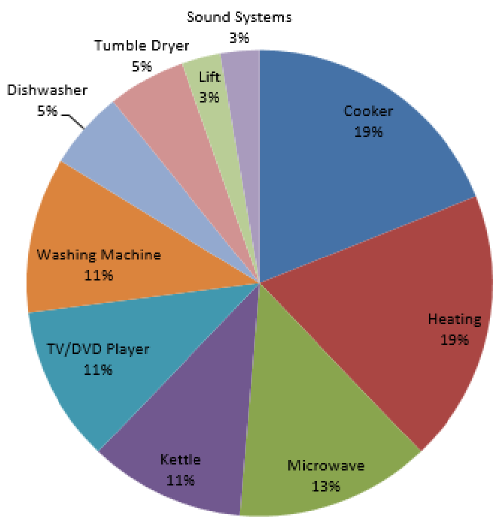

Figure 23: Challenging household appliances

Tasks outside the home: The most difficult task was using public transport, as illustrated in Figure 24. Users commented that they did not have confidence to use public transport on their own due to it not being always accessible for powerchairs. Stays in overnight accommodation were the second most challenging task outside the home with comments that it was very difficult to find suitable wheelchair-accessible accommodation.

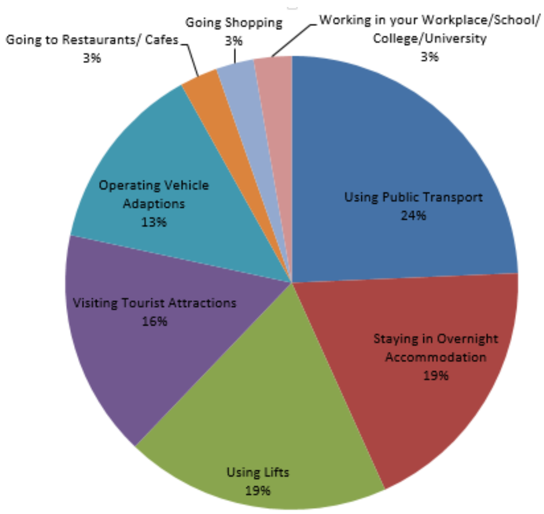

Figure 24: Challenging outdoor tasks

Weather Conditions: Figure 25 illustrates that the most challenging weather conditions to operate a powerchair under was snow and rain, with 29% and 27% of users respectively. Users commented that this was due to powerchairs becoming stuck in the snow or out of control with low grip levels. Night was only challenging to operate powerchairs that were not equipped with lights where pavement kerbs were not visible to users.

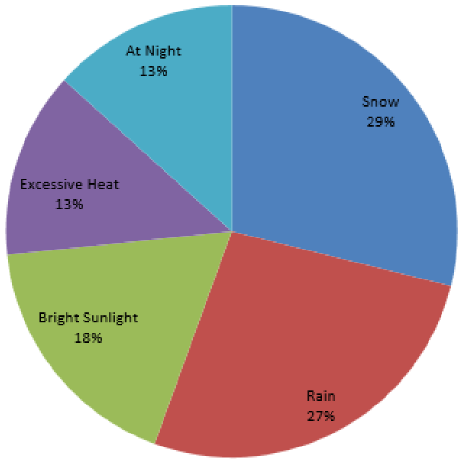

Figure 25: Challenging weather conditions

Technologies: Figure 26 shows that 48% of users stated a smartphone operated by either touch or head tracking had the greatest potential. A smartphone controlled by voice was only popular with individuals who did not have reduced speech ability. Head mounted displays and digital pens were the least popular technology at 10% and 4% respectively.

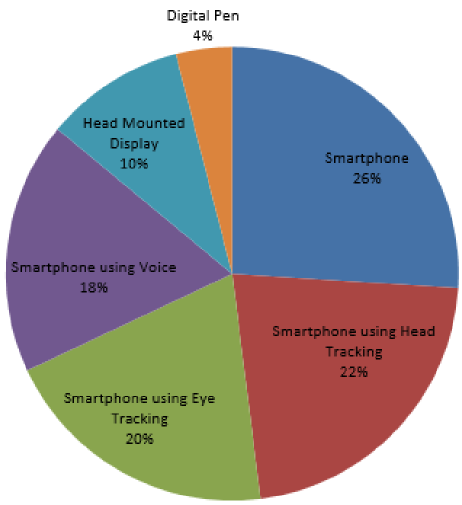

Figure 26: Potential useful technologies

Using a combination of online and paper-based surveys and semi-structured interviews with a user group of people with reduced physical ability, user requirements were established in terms of challenging tasks and potential application of technologies that could be incorporated into a framework.

4.4 Manufacturer Requirements

The manufacturer requirements for technologies to be incorporated into a framework were elicited through iterative engagements via e-mail and Skype with Dynamic Controls (New Zealand). Dynamic Controls were approached due to being a recognised global manufacturer of powerchair controllers and as the author had previously collaborated with the company during the original installation of ATRS. The produced requirements specification from Dynamic Controls (Appendix F) was the basis to define Volere requirements. Each requirement was assigned a unique identifier with the abbreviation, 'FR', being used to describe Functional Requirements, whereas Non-functional Requirements are denoted by an abbreviation according to type (Table 4).

Table 4: Selected Non-Functional requirement types

Type	Abbreviation
Interoperability	IR
Reliability	RR
Safety	SFR
Usability	UR

The Volere Requirements Shell was created by selecting the attributes that were relevant, therefore the 'Event/Use Case' and 'History' attributes were omitted as the requirements did not relate to a Use Case and these requirements had not been previously defined. An additional Priority attribute was added to enhance the requirement shell by identifying which requirements were imperative. The MoSCoW scale was used to prioritise the requirements as: Must, Should, Could and Won't (Clegg and Barker 1994). The selected attributes are described in Table 5.

Table 5: Selected Volere attributes

Attribute Name	Description (Robertson and Robertson 2004)
Requirement ID	A unique identifier of the requirement
Requirement type	'The type from the template'
Description	'A one sentence statement of the intention of the requirement'
Rationale	'A justification of the requirement'
Source	'Who raised this requirement?'
Fit criterion	'A measurement of the requirement such that it is possible to test if the solution matches the original requirement'
Customer satisfaction	'Degree of stakeholder happiness if this requirement is successfully implemented. Scale from 1 = uninterested to 5 = extremely interested'
Customer dissatisfaction	'Measurement of stakeholder unhappiness if this requirement is not part of the final product. Scale from 1 = hardly matters to 5 = extremely

	displeased'
Dependencies	'A list of other requirements that have some dependency on this one'
Conflicts	'Other requirements that cannot be implemented if this one is'
Supporting materials	'Pointer to documents that illustrate and explain this requirement'

Using the above attributes, Volere requirements were established for technologies to be incorporated into a framework and the framework itself. The four key technology and framework-related requirements are shown in the Requirements Shells below while the remainder are defined in Appendix G.

Technology Manufacturer Requirements

Requirement FR1

Requirement ID:	FR1
Requirement type:	Functionality
Description:	A technology shall not be a single solution to fit multiple needs.
Rationale:	Each end user will have different needs so it will not be possible to develop a single version of a technology that meets a range of abilities. It is important that a technology is an adaptable solution that can be customised, e.g. having only one modality interaction will not be sufficient to cater for all abilities, having multiple modalities will increase the potential of the technology to improve Quality of Life.
Source:	Dynamic Controls
Fit criterion:	A variety of abilities are supported by the technology. The technology increases the Quality of Life for a range of tasks in varying environments.
Customer satisfaction:	4
Customer dissatisfaction:	4
Priority:	Must
Dependencies:	None
Conflicts:	None
Supporting Materials:	Dynamic Controls requirements specification.

Requirement RR1

Requirement ID:	RR1
Requirement type:	Reliability
Description:	A technology shall be robust against potential technical failures.
Rationale:	As the users be dependent on the technology in their daily lives, mechanisms to cope with technical failures shall be implemented.
Source:	Dynamic Controls
Fit criterion:	Suitable system redundancy exists so that there is at least one alternative interaction method should a technology fail. The user is not reliant upon one form of technology.
Customer satisfaction:	3
Customer dissatisfaction:	5
Priority:	Must
Dependencies:	FR1, IR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Framework Manufacturer Requirements

Requirement FR2

Requirement ID:	FR2
Requirement type:	Functionality
Description:	A framework shall map the variety of interaction methods for technologies to the abilities of the user.
Rationale:	Depending on their ability, the users will have preferences over the technology interaction method.
Source:	Dynamic Controls
Fit criterion:	A framework enables a list of technologies that can be integrated with powerchairs to be viewed. Only technologies that are suitable for the user's abilities are suggested by the framework.
Customer satisfaction:	3
Customer dissatisfaction:	3
Priority:	Must
Dependencies:	FR1, UR1, IR1, FR3.
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

The collaboration with Dynamic Controls resulted in the definition of seven technology-based and two framework-related manufacturer requirements. These requirements were combined with the user requirements to inform the development of a framework to recommend technologies.

4.5 Summary

The requirements for a framework and the incorporated technologies were elicited through surveys and semi-structured interviews from a user group of people with reduced physical ability, as well as from industry by forming a collaboration with an assistive technology manufacturer. The user requirements identified the challenges that the community currently encountered in their daily lives and determined the technologies to investigate further in feasibility trials and controlled usability evaluations. These trials and evaluations will contribute to a framework in terms of the type of interaction modalities and technologies that can be incorporated. Based on their expert knowledge in the domain, the manufacturer identified the requirements that a framework and the incorporated technologies need to meet to ensure successful exploitation and adoption by the assistive technology and healthcare domains. Only technologies that are deemed to meet the manufacturer requirements for assistive technologies will be considered for trials and evaluations in order to maximise their applicability to a framework.

Chapter 5 Research Results (ii) - Feasibility Trials

5.1 Introduction

The purpose of the feasibility trials was to assess the usability of the technologies without the involvement of the user community and to determine suitable technologies for inclusion in a framework. The feasibility trials are an exploratory phase of the research that were solely conducted by the author, with the exception of Trial 1 which involved a participant.

The first feasibility trial investigated an electroencephalograph (EEG) using a Brain Products 64-channel actiCAP (Brain Vision UK 2017) to monitor brain activity when performing body movements to identify whether the movements could be used as triggers for functions. The second and third feasibility trials involved Tracking-Learning–Detection (TLD) as a form of facial feature tracking. Both Versions 1.0 (Kalal et al. 2012) and 2.0 (TLD Vision s.r.o. 2016) were trailed on a Windows computer to investigate the differences between the first and second generation of the real-time tracking algorithm and the suitability of using TLD via the forward-facing camera of a smartphone to navigate a user interface. iOS Switch Control (Apple Inc. 2016) was the subject of the fourth feasibility trial, whereby the accessibility feature was used to track head movements. The final trial involved smartglasses to provide interaction through a head mounted display as an alternative for users who are not able to use touch or joystick interaction. A Recon Jet (Recon Instruments 2016a) was used for this trail, which is a commercially-available head mounted display designed for cyclists. The aims, procedures and results of each feasibility trial are presented in this chapter. The results of the trials identified the technologies that have the greatest potential to improve Quality of Life and were tested with the user community in the controlled usability evaluations described in chapter 6.

5.2 Trial 1: Electroencephalogram (EEG)

Aim: To determine how reliably EEG technology detects brain activity in response to movements that could be used to interact with SmartATRS.

Procedure: A 64-channel actiCAP was used for this trial but only 32 channels were connected to the participant. This was due to the time required in connecting the electrodes and as this was an initial exploratory trial to determine the suitability of EEG. After receiving consent from the participant, the first stage was to attach the actiCAP. To ensure that good electrical contact was made, the participant did not to use any products on their hair prior to the trial. The circumference of the participant's head was measured so that an appropriate size of actiCAP was used. After attaching the actiCAP, each of the electrode connections were cleaned with alcohol with a cotton bud to ensure that good electrical contact was made. A sand-based gel was applied to each of the 32 electrodes to remove any dry skin. The gel was administered using a syringe into the electrode connections. It was ensured that the central electrode connection received a sufficient amount of gel, as this electrode creates the earth connection. The electrodes were connected by following a diagram showing the electrode locations with unique numbers and colours (Bobrov et al. 2011). The first 32 locations were coloured in green and the second 32 were shown in white therefore, only the green connections were utilised for the trial. The connections were not numbered consecutively around the head, so care had to be taken ensure that all electrodes were attached correctly. The participant was asked to verify that none of the electrodes were causing any discomfort and any adjustments were made as required. A second clear gel was applied to each electrode administered by a syringe. All instruments used during the preparation stage were then cleaned to ensure that all of the gel was removed and none was left on the instruments. The preparation stage took 35 minutes and the fitted actiCAP can be seen in Figure 28.

Figure 27: Participant performing tongue and mouth movements whilst wearing an actiCAP

The actiCAP was connected to an amplifier using a serial connector and was linked via a fibre optic cable to a Windows computer installed with the BrainVision Recorder software (Brain Products GmbH 2017) to view and record the brain activity measured by the EEG. Once the actiCAP received communication with the computer, each electrode lit up showing the quality of the electrical connections. If the electrodes were lit in green, a good communication had been made, whereas poor connections were shown in red. BrainVision Recorder provided a facility to view the electrical connection quality of each electrode in terms of resistance. There was only one electrode making poor contact, which was caused by hair obstructing the connection from the electrode to the skull. Once the hair had been moved away from the electrode, the resistance reduced and a good contact was made.

The room was darkened so that there was a reduced chance of increased brain activity caused by the ambient light. A set of predefined actions were performed by the participant with each action being repeated over two-minute durations and the brain activity recorded by the software in separate files. A screenshot of one recording is shown in Figure 28.

Figure 28: An example EEG recording

Each line represents the electrical activity measured by each electrode and the electrodes are ordered in terms of position on the skull. Brain activity data is updated in real time and in this particular screenshot, electrodes T7 and T8 (attached to the ear lobes) show increased brain activity illustrated by the larger amplitude of the waves.

After the trial, the actiCAP was disconnected from the computer and the connections to each electrode were unplugged. The actiCAP was removed from the participant's head in a backwards motion, which was difficult due to the gel pulling on the participant's hair. The hair required washing following the experiment and the actiCAP was washed thoroughly to prevent the gel from causing corrosion to the electrodes when not in use.

Results: The participant performed tasks involving eye, head and mouth movements, as well as speaking commands in order to determine the reliability of detecting fluctuations in brain activity.

The first set of tasks was a series of vertical and horizontal eye movements, with a 3-second movement every 6 seconds. All eye movements resulted in increased activity from the electrode positions toward the front of the brain and could be reliably detected, except diagonal movements (e.g. moving the eyes to the top-right corner), which caused the same brain activity as horizontal movements. It could therefore be deduced that diagonal eye movements were not a reliable interaction method.

To investigate the effect of blinking, the participant blinked for 3 seconds every 6 seconds. The blinks could also be reliably detected, proving that this would be a feasible means to interact. Experimentation was performed to determine whether a longer blink (i.e. closing the eyes for six seconds) could be an alternative interaction method. However, a long blink produced brain activity in the rear electrodes indicating that the participant was becoming sleepy and consequently would not be a suitable method. The participant also winked by closing one eye for 3 seconds every 6 seconds; both eyes were experimented with and could be reliably detected. It was crucial not to move the head whilst winking, as this introduced 'noise' to the brain activity. The action proved difficult to perform due to lengthy timing issues and therefore, the test was found to be unreliable.

Horizontal and vertical head movements produced noticeable fluctuations in brain activity, however were not reliable. However, these could have been produced by the wires to the electron being stretched when the head moved rather than by the brain activity. As the stretching created noise in the brain signals, it was concluded that head movements would not be suitable. Based on the range of tongue movements performed by the participant, external actions could not be as reliably detected as internal movements, which were also less conspicuous. In particular, biting the tongue between the teeth proved reliable and could be a potential interaction method. Another mouth movement that was investigated was smiling; this showed an obvious change in brain activity indicating that it would be a reliable interaction method. The brain activity produced from speaking commands was found to be reliable depending on the pronunciation of the commands spoken. Commands that involved larger mouth movements such as "out", "snake" and "zebra" could be reliably detected. Therefore, speech could be a means for interaction, but the commands would have to be chosen specifically and may not be relevant to the action performed. Table 6 summarises the actions performed during the trial and their detection reliability:

Table 6: Reliability of head, eye and tongue movements

Actions	Reliability
Moving eyes upwards	Reliable
Moving eyes downwards	Reliable
Moving eyes right	Reliable
Moving eyes left	Reliable
Moving eyes to top left	Unreliable – detected as a horizontal movement
Moving eyes to top right	Unreliable – detected as a horizontal movement
Moving eyes to bottom left	Unreliable – detected as a horizontal movement
Moving eyes to bottom right	Unreliable – detected as a horizontal movement
Moving head upwards	Unreliable – caused electrode wires to stretch
Moving head downwards	Unreliable – caused electrode wires to stretch
Moving head right	Unreliable – caused electrode wires to stretch
Moving head left	Unreliable – caused electrode wires to stretch
Moving tongue right	Reliable
Moving tongue left	Reliable
Moving tongue outside mouth	Unreliable – no obvious change in brain activity
Biting tongue between teeth	Reliable
Short blink (2 seconds)	Reliable
Long blink (5 seconds)	Unreliable – induced brain into a 'sleep state'
Winking	Reliable but difficult to perform
Smiling	Reliable
Speaking commands	Reliable on words that created noticeable mouth movements

Based on these findings, the following list of actions were recommended to enable EEG to interact with technology:

- Moving tongue left and right
- Moving eyes up, down, left and right
- Biting tongue between teeth
- Blinking eyes

Feasibility Trial 1 identified the capabilities and limitations of EEG technology through the application of an actiCAP. It was discovered that certain movements could be reliably detected and therefore, can be used as triggers for functions, facilitating incorporation into a framework. To investigate alternative forms of tracking movements, Tracking-Learning-Detection (TLD) 1.0 was investigated in Feasibility Trial 2.

5.3 Trial 2: Tracking-Learning-Detection 1.0 (TLD 1.0)

Aim: To determine whether TLD 1.0 provided sufficient accuracy to be used for head-based interaction with SmartATRS.

Procedure: The TLD 1.0 algorithm was initially installed on a Windows operating system, which required four applications to be installed: MATLAB (with the Image Acquisition Toolbox, Image Processing Toolbox, Statistics Toolbox and Signal Processing Toolbox extensions), Microsoft Visual Studio and OpenCV2.2. MATLAB was required to run TLD 1.0 and Visual Studio was needed to build OpenCV2.2 (the algorithm was only compatible with Version 2.2).

The first stage of the installation was to install Python libraries, as OpenCV was written in Python and needed to be compiled before use. The CMake tool was used to create the Visual Studio project files from the source files. When using CMake, the required packages of OpenCV were selected as not all packages were required for TLD 1.0. Creating the project files allowed OpenCV to be configured using Visual Studio and the binary files to be created which were accessed by TLD 1.0. The Visual Studio solution file created by CMake was opened and initialised by adding the included files to the solution. The whole solution was built using Visual Studio in both Debug and Release modes. This created a 'bin' directly containing the binary files required for TLD 1.0. The Install project within the solution was built in Release mode to create the necessary header files. The environment variable for the OpenCV Dynamic Linked Libraries (DLL files) was created and inserted into the registry using command prompt. The link to the variable was added to the 'PATH' environment variable in the operating system.

The TLD 1.0 source files were downloaded that contained the MATLAB mex files that run the tracking algorithm. Within MATLAB, the mex compiler was setup to the Visual Studio 2010 complier by using the '*Run: mex –setup*' command. After the complier was setup, the OpenCV paths within the compile file of TLD 1.0 were edited to suit the installation path of OpenCV.

TLD 1.0 was compiled by running the '*compile.m*' file. In MATLAB, TLD 1.0 could be executed in one of two methods: '*run_TLD*' executed the algorithm but did not produce images of the tracking process, whereas '*run_TLDdemo*' produced images of the tracking process, so it could be recorded. For the purposes of this feasibility trial, '*run_TLDdemo*' was executed.

Results: The TLD algorithm was installed with a sample video where a motocross bike was tracked, as shown in Figure 29.

Figure 29: TLD 1.0 tracking a motocross bike

It could be seen that TLD 1.0 created a bounding box around the bike and continued to track the object as it changed position in the video frames. When the bike went out of view and reappeared, TLD 1.0 remembered the object and continued to track it. The position of the object in each frame was defined by XY co-ordinates and TLD 1.0 outputted the co-ordinates to a text document in real-time. At the end of the video sequence the text document was populated with the co-ordinates of the bike throughout the sequence.

Two 'Getting Started' tutorials from the TLD 1.0 website were then performed. The first tutorial utilised a web camera and executed the TLD 1.0 algorithm on the live stream from the camera. A Universal Serial Bus (USB) webcam was used and the Windows drivers were installed. The 'winvideo' adapter was installed into MATLAB to enable images to be acquired from the webcam. By using the '*a=imaqhwinfo ('winvideo'); a.DeviceInfo*' command, the supported video format for the webcam could be determined. The supported format was added into the '*initcamera.m*' file so that TLD 1.0 was setup correctly. Tracking from the live camera stream instead of the bike video was enabled by setting the camera variable in '*run_TLD.m*' to 1. When TLD 1.0 executed, a still image from the webcam was displayed where a bounding box could be draw around the object to be tracked. To train the algorithm, a box was drawn around the nose of the tester, therefore representing the facial feature to track. Drawing the box involved dragging the cursor to create a shape totally covering the target. The algorithm was tested by viewing the live stream from the camera. The nose was accurately tracked and could be followed when the tester changed position (as shown in Figure 30), e.g. if the tester left the field of view and re-entered TLD 1.0 continued to track the nose. When another participant was in the field of view of the camera, TLD 1.0 did not track their nose, as it had not been trained to do so. When multiple participants were in the field of view, only the nose of the trained participant was tracked. It is noted that this trial was not conducted in a controlled environment (with interference from background object), however, it was necessary to trial TLD in a real world environment to obtain an accurate assessment of performance. The algorithm did not experience complications due to background objects as the nose was successfully tracked.

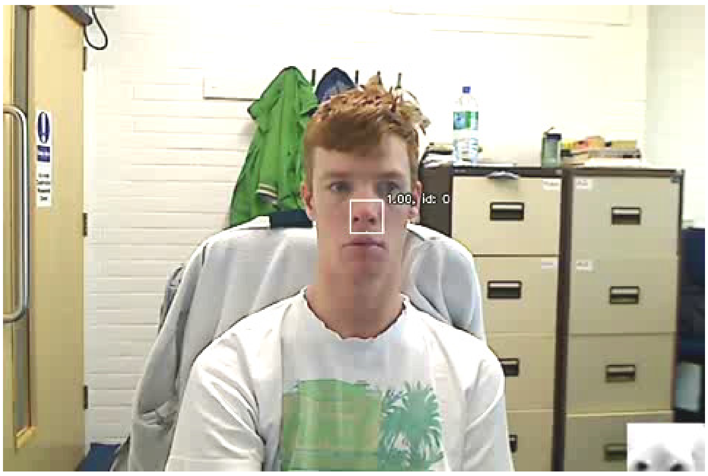

Figure 30: TLD 1.0 tracking the nose

The second tutorial tracked an object in a custom movie file. Movie files could not be directly imported into TLD 1.0, but have to be converted into a frame image sequence consisting of a series of Joint Photographic Experts Group (JPEG) image files. Video editing software was used to convert an Audio Video Interleave (AVI) video file into an image sequence. To test TLD 1.0, a skiing movie was used, as it contained a fast moving object that is viewed from different angles. The two-minute movie was converted into 1000 JPEG image files and placed in the input folder of TLD 1.0, replacing the image files of the motorbike movie. No additional changes were made to the source code of the TLD 1.0 and the algorithm was executed as before. A bounding box was drawn around the skier and TLD 1.0 processed each frame individually and therefore, it was relatively time-consuming to process the entire video sequence. The object tracking in the movie was challenging as the object was changing direction and speed as well as being obstructed from the field of view by other skiers. Nevertheless, TLD 1.0 was able to track the object with good accuracy even when the object was some distance away. Although tracking an object in a video would not be useful as an interaction method, it demonstrated the robustness of the algorithm to track different types of objects.

Feasibility Trial 2 demonstrated that TLD 1.0 could accurately detect a nose, which could be used as a form of face tracking. However, it was only possible to test the algorithm on a Windows platform as it was not feasible to install MATLAB and the other required software on a smartphone. As the second generation of the algorithm did not require the MATLAB environment, it was the subject of Feasibility Trial 3.

5.4 Feasibility Trial 3: Tracking-Learning-Dectection (TLD 2.0)

Aim: To analyse the performance and suitability of TLD 2.0 for head-based interaction with SmartATRS.

Procedure: The experiment was performed using a compiled Software Development Kit (SDK) version of TLD 2.0, as the source code could not be obtained from TLD Vision until it was proven that TLD 2.0 would be suitable. The SDK consisted of a zipped package containing an executable file and the DLL files required for OpenCV2.2. Visual Studio Redistributable 2013 was required and obtained from the Microsoft website. As OpenCV2.2 was already installed from the TLD 1.0 trial, the TLD 2.0 SDK could be executed from a command prompt by running an executable file. This was a major advantage over TLD 1.0 that ran in the MATLAB environment. The main menu for the TLD 2.0 demo was shown in a command prompt (Figure 31).

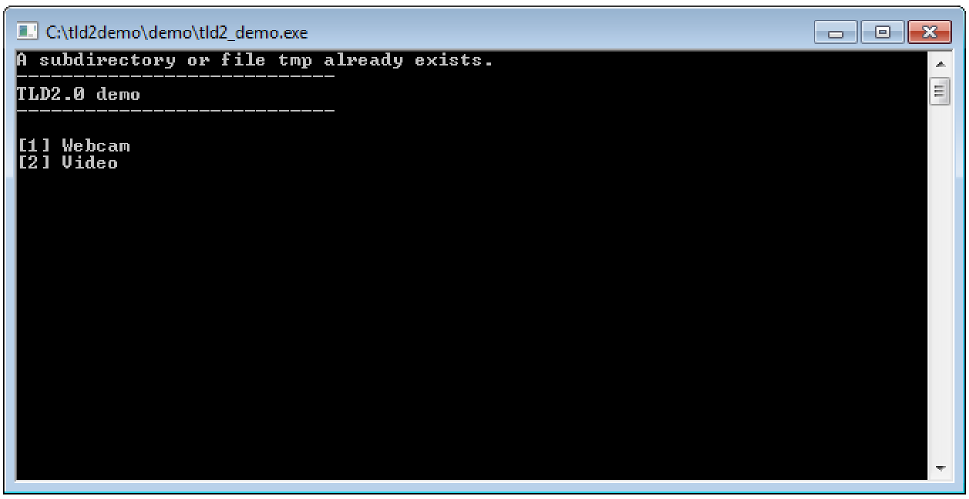

Figure 31: TLD 2.0 Demo

The menu allowed the data source to be selected from two options, 'Webcam' and 'Video', by entering '1' or '2'. Selecting 'Webcam' allowed the data stream from a USB webcam to be utilised by TLD 2.0. Selecting 'Video' enabled an AVI file to be processed by an algorithm. This file was located in the TLD 2.0 directory and named 'data.avi'. This was an advantage over TLD 1.0 where only a series of JPEG images could be imported. A demonstrating video was included with the SDK, but a user-created video could be processed by renaming the file to '*data.avi*' and replacing the original file. The encoding format of the video was not important, as TLD 2.0 selected the correct codec automatically and scaled down the video if it was above 640x480 pixels.

Within the TLD 2.0 directory, a '*\tmp*' sub directory contained a text file with the output coordinates of the algorithm.

Results: The Object Tracking video contained within the SDK was used to initially demonstrate TLD 2.0. '*[2] Video*' was selected from the main menu and the application opened a window containing the first frame of the sample video, a motocross sequence. The data stream was frozen so that the object(s) to track could be selected. The target object(s) were selected by drawing bounding boxes around the objects. Multiple objects could be selected and the bounding boxes needed to tightly surround the target, as shown in Figure 32.

Figure 32: Multiple target objects selected in TLD 2.0

Each target object was given an identification number with the first object numbered '0'. Initially, it was more difficult to draw the boxes in TLD 2.0 than in TLD 1.0, as the method was different. When drawing the bounding box in TLD 2.0, a small square was produced by clicking on the target. To expand the square the cursor was moved in any direction. This made producing small bounding boxes easier, however producing large boxes was less logical than TLD 1.0, where the box was drawn from a vertex. Once familiar with the method, it became more usable. The head of the rider was selected to demonstrate the object tracking. The SDK contained parameters that could be controlled during runtime, as shown in Table 7. Each parameter can be modified using the shortcut keys.

Table 7: TLD 2.0 parameters

Command	Shortcut	Description
Freeze	F	Continuously load the last image of the video screen so that targets can be selected.

Pause	P	Pauses TLD 2.0 so that no tracking occurs.
Rotate	R	By default, TLD 2.0 is only able to detect the target when in upright position. When rotate is set to false, rotation-invariant detection is active. Therefore, objects are tracked in all positions.
detect	D	Enables the detection capability of TLD 2.0. It is turned on by default.
Learn	L	Enables the learning capability of TLD 2.0. It is turned on by default. Disabling the parameter increases performance but TLD does not learn from its errors.
Id	+/-	Switches between the active targets on the frozen frame. Active targets are coloured, inactive targets are grey.
Kill	K	Deletes the active target.
draw_pex	P	When enabled, an image of each positive detection of the target(s) are displayed in the top right of the screen.
draw_target	T	When enabled, an image of each target is displayed in the bottom right of the screen.
draw_info	I	When enabled, the number of scanned locations is displayed in the bottom left of the screen.
save_input	I	Saves screenshots of the TLD 2.0 input to the /tmp directory
save_output	O	Saves screenshots of the TLD 2.0 output to the /tmp directory

When multiple targets were selected, it was possible to switch between them by using the '+/-'keys. Any target could be deleted (killed) by pressing the 'k' key. By default, TLD 2.0 did not save the processed frames, but this could be enabled by pressing the 'O' key. This created a series of Portable Network Graphic (PNG) images in the *tmp* directory. For the purposes of this experiment, all output images were saved so that the performance with TLD 2.0 could be analysed after execution.

The tracking was executed by pressing the 'f' key that unfroze the data stream. The video sequence and TLD 2.0 was able to track the motocross rider, as he progressed round a course containing jumps. When the algorithm lost the target (e.g. between jumps), it resumed tracking once it was visible. The content of the bounding box was shown in the bottom right-hand corner of the screen and updated in real-time. This was a particularly useful feature to view the data that the algorithm was processing. The performance was good and showed an improvement over TLD 1.0 in terms of the time taken for TLD 2.0 to resume tracking the object after it had been lost.

In the first tutorial, a USB webcam was connected to the computer and the participant sat in front of the webcam. Option 2 was selected from the main screen and the application opened a window displaying the frozen data stream from the webcam where a target could be selected. A bounding box was drawn around the participant's nose and tracking was initiated. As in the TLD 1.0 experiment, the participant moved their head in various directions, as well as leaving the field of view. The performance was good and again showed an improvement over TLD 1.0 on resuming tracking.

For the second tutorial, the skiing video used in the TLD 1.0 experiment was placed into the TLD directory as an AVI file. Various aspects of the skier[4] were tracked; including parts of the head, body and equipment as well the entire skier, shown in Figure 33.

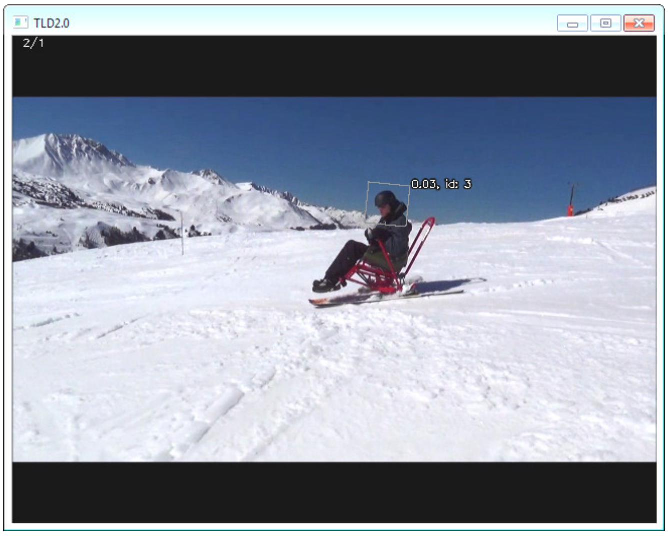

Figure 33: TLD 2.0 tracking a skier

An advantage of TLD 2.0 was the video was played in real-time rather than individual frames, as with TLD 1.0. Therefore, processing was performed considerably quicker. However, TLD 2.0 did not perform as reliably as TLD 1.0. When the tracked object was lost, tracking was not resumed when the object re-entered the field of view. Also, other objects in the video were tracked instead of the target object. The target object was only tracked when it was in the same orientation as the initial target. This was different to TLD 1.0, where the target was still tracked even when the orientation changed.

It was discovered that setting the '*rotate*' parameter to FALSE, improved the tracking ability of TLD 2.0 as the camera taking the video was not static (unlike the webcam). With the '*rotate*' parameter set, the tracking performance of TLD 2.0 was comparable with TLD

[4] The author.

1.0 and there were no false detections of other objects in the video. However, TLD 2.0 had the advantage that the video was processed in real-time rather than frame-by-frame.

Feasibility Trial 3 established that TLD 2.0 could detect the face as reliably as TLD 1.0, but had the advantage of being an executable file. TLD 2.0 also resumed tracking more effectively than 1.0 when the target re-entered the field of view. However, through investigations, it was concluded that a smartphone implementation of TLD 2.0 would not be feasible due to requiring knowledge in C++ programming that the author did not possess. As a result, alternative technologies were investigated that provide a means to track facial features and therefore, iOS Switch Control was the subject of Feasibility Trial 4 to determine the capability of tracking the entire head.

5.5 Feasibility Trial 4: iOS Switch Control

Aim: To ascertain whether iOS Switch Control would be a feasible interaction method to assist users who have difficulty interacting through touch, joystick or voice.

Procedure: For part one of the experiment, Switch Control was used in Item Mode with the left head movement switch set to 'Move to next item' and the right head movement set to 'Select item'. In the second part, Item Mode was also used but the left head movement switch was deleted, only leaving the right head movement as 'Select item'. The Auto Scanning feature was enabled so that each item on the user interface was highlighted sequentially and the user could select the focussed item by using the right head movement. The configuration of Auto Scanning was set to:

- ‘Auto Scanning time’ – 1 second
- ‘Pause on the first item’ – off
- ‘Number of loops’ – 4

An ‘Auto Scanning time’ was selected through a trial and improvement method whereby one second was found to be sufficient to allow a user to make a selection but not be too time-consuming to navigate to the buttons at the bottom of the user interface.

Part 3 consisted of experimenting with the scanning mode of Switch Control set to Point Mode (Pretorian Technologies 2014), which allows the user to select an exact point on the user interface. The right head movement remained as the Select switch and the left head movement was unassigned. Once Switch Control was configured in Point Mode, it was set as the default Scanning Mode and therefore, did not revert back to Item Mode, unless selected through the Settings menu.

After Switch Control was enabled, it was firstly used to navigate around iOS (referred to as ‘iOS’ results) and secondly to navigate around the SmartATRS GUI (entitled ‘SmartATRS’ results). For purposes of the experiment, the GUI was a simulation of ATRS and not connected to the vehicle.

Results:

Part 1: Item Mode (Auto Scanning Off)

iOS: The device was set to the home screen and Switch Control selected the first row of items in a single group. To enter the group, a right head movement was required and subsequent left head movements were required to navigate within the group. It was found that with Auto Scanning off, there was a steep learning curve as multiple head movements were required to step through each item on the interface followed by an additional movement to select an item. This increased the time and number of head movements taken to reach the items in the lower half of the display.

A noticeable observation was that large head movements were required in order to be recognised, therefore requiring significant physical effort to be exerted. In the Switch Control configuration, the head movement sensitivity could be adjusted to high or low (default). By changing the sensitivity to high, smaller head movements were recognised, therefore reducing the physical effort. The second observation was when an item was selected, an additional menu was displayed so that the type of selection could be specified (i.e. 'tap', 'hold' or 'drag'). This created additional complexity, as typically only a tap selection is required. Enabling the Auto Tap feature in the configuration simplified the selection process by always using the tap selection and not displaying the menu. Auto Tap significantly improved the usability of Switch Control for basic selection functions.

The border around the highlighted items was quite small and would be difficult to see in an outdoor environment. However, Switch Control had the option to use a large cursor with a choice of colours to improve the visibility of the currently highlighted item which was deemed suitable for an outdoor environment.

Enabling the speech feature of Switch Control further assisted with navigation, as the name of the currently highlighted item was spoken. This had the advantage of creating positive feedback to the user on which item is highlighted. The feedback would be useful in outdoor environments where it may be difficult to read the display.

A disadvantage of having the Auto Scanning disabled was that a large number of repetitive head movements were required to navigate around the interface, which may produce neck strain if used for long periods of time.

SmartATRS: SmartATRS could successfully be controlled using Switch Control with Auto Scanning disabled; however, it required a considerable number of head movements to navigate around the GUI. When the GUI was first loaded, the initial highlighted item was the webpage title and the user was required to skip through the Safari toolbars (i.e. URL and search) before reaching the GUI. Once this was reached, each icon had to be skipped through before the function buttons were highlighted. This involved eight head movements in order to reach the first function button, requiring a considerable amount of physical effort and was very time-consuming. Once a function button was highlighted, it could easily be selected using the right head movement.

Due to the number of repetitive head movements, Switch Control with Auto Scanning disabled, was deemed to be unsuitable for SmartATRS.

Part 2: Item Mode (Auto Scanning On)

The Auto Scanning was enabled and settings recommended in Part 1 were retained.

iOS: Switch Control automatically navigated around the user interface, highlighting each item sequentially. A disadvantage of Auto Scanning was that by default, each item was highlighted for one second before moving to the next item. This proved to be too quick, as when users had familiarised themselves with the highlighted item, the scanner had moved onto the next item. The Auto Scanning was therefore increased in a trial-and-improvement method, whereby the duration was increased in 0.05 second intervals. Two seconds were found to be sufficient to make a selection without compromising navigation time. With the increased Auto Scanning time, Switch Control was more usable, as only a right head movement was required for selection.

A second disadvantage was that the user was not in complete control of the interface, as it relied heavily on the timing of the selection to prevent an incorrect selection being made. There would therefore be a greater chance of inaccurate selection compared to with the Auto Scanning feature disabled, when users could step through the items in their own time.

SmartATRS: When the SmartATRS GUI was loaded, the scanner began from the Safari toolbars and skipped through each toolbar sequentially. Next, the scanner progressed through the icons on the GUI before reaching the function button. This was time-consuming, as the scanner highlighted each item for one second, resulting in an eight-second delay before the first SmartATRS function could be selected. Function selection through the right head movement was successful; however, it was easy to either miss or perform an inaccurate selection due to a slow reaction time. When a function was missed, users have to wait for the next time the scanner cycled around the GUI, creating a 15-second delay. This would be frustrating to users, as well as being a potential safety risk in an emergency stop situation.

The Auto Scanning feature improved the usability of Item Mode and therefore, made it a possible interaction for SmartATRS. Through continued use users would become accustomed to the selection process and this would reduce the risk of inaccurate or missed selections. As it was possible to reduce the Auto Scanning duration (the time in which the scanner pauses on each item) for experienced users, the time for the scanner to reach the GUI would be reduced.

Part 3: Point Mode

When Switch Control was in Item Mode, Point Mode was activated via the Settings menu. The Auto Tap feature remained enabled, so that tap selection was activated using the right head movement switch.

iOS: Switch Control scanned the screen vertically from left to right. When the scanner reached approximately the desired position, the user first made a right head movement to enter a fine tune of the vertical position of the scanner until the next right head movement was made to set the horizontal position. Switch Control then scanned the screen horizontally from top to bottom. To set the horizontal position, a right head movement was made when the scanner reached the desired location. The point nearest to the intersection was selected.

Initially, the screen was scanned too quickly, increasing the chance of making an inaccurate selection. However, in the settings menu, the scan speed could be decreased. Although this increased navigation time, it improved accuracy of selection. Once users become accustomed to Point Mode, the scanning speed could be increased to improve performance.

SmartATRS: Navigating through the SmartATRS GUI using Point Mode proved to be the most efficient. No additional time was used to navigate through the Safari toolbars as an exact location on the GUI could be selected. Using the slower scanning speed decreased the risk of selecting an incorrect function button. The Emergency Stop function could be easily selected through Point Mode as the button had a large width. Therefore, it was not essential to select a precise horizontal position as the button covered almost the entire width of the interface.

Point Mode was identified as being the most suitable for operating SmartATRS because there was no delay in scanning through the items on the interface as identified in Item Mode. Although Point Mode is dependent on the timing of the selection, it can be easily customised to suit users' abilities.

Feasibility Trail 4 established that the Switch Control accessibility feature was an effective method to interact with an iOS device through left or right head movements. Using the feature in Item Mode was concluded to be unsuitable due to the number of repetitive movements required and the process being time-consuming. Point Mode was found to be the most usable, as it was possible to select any position on a user interface with four head movements in a minimal selection time. To determine the suitability of head-mounted technologies as alternative interaction mediums for people with reduced physical ability, a Recon Jet smartglass was tested in Feasibility Trial 5.

5.6 Feasibility Trial 5: Smartglass

Aim: To ascertain whether a smartglass (Recon Jet) would be a feasible interaction method as an alternative to a smartphone or tablet.

Procedure: In order to use the Recon Jet with SmartATRS, a specific application needed to be developed, due to the standard applications on the device not being suitable. As the Recon Jet operating system (ReconOs) uses an Android platform, a Windows computer was set-up with the Android Debug Bridge (ADB); a command line tool that enables communication with the Recon Jet.

The USB Debugging feature on the device had to be enabled via the settings menu in order for the Recon Jet to communicate via the ADB. The device would then be connected to the PC where the ADB driver, created by Recon Instruments, was installed. A link to the ADB driver was added to the PATH system environment variable so that the driver could be executed via the command prompt without having to navigate to the directory containing the driver. To verify that the Recon Jet was successfully connected to the PC, the command '*adb devices*' was executed in the prompt and showed the serial number of the Recon Jet to indicate that it was successfully connected.

One of the sample applications provided in the SDK was 'OpenURI', which enabled any URL to be opened when the application was executed. The Android application consisted of an 'Uri' parameter in which the URL of the webpage to be opened is assigned, in this case the IP address of the SmartATRS GUI located on the relay board. A browser is then launched and is parsed with the Uri parameter so that the browser on the Recon Jet loads the webpage when the application is executed. The Android code is shown in Figure 34.

```
public class MainActivity extends AppCompatActivity {

    @Override
    protected void onCreate(Bundle savedInstanceState) {
        super.onCreate(savedInstanceState);
        Uri uriUrl = Uri.parse("http://192.168.0.207/ProXR/MyPageJet.html");
        Intent launchBrowser = new Intent(Intent.ACTION_VIEW, uriUrl);
        startActivity(launchBrowser);
    }

}
```

Figure 34: Main body of the OpenURI application for the Recon Jet

To load the SmartATRS GUI on the Recon Jet, the device was connected to the Wi-Fi network through the settings menu. This was challenging as a small on-screen keyboard had to be used to enter the network password, however, this only needed to be performed once, as the network was remembered. Once connected, the OpenURI application was executed via the Apps menu, which opened the GUI.

Results: Due to the small size of the display compared to a smartphone or tablet, one button filled the entire display, thus identifying that a specific GUI would need to be created for the Recon Jet with smaller buttons. The interface was modified through a trial-and-improvement method using Visual Studio and uploaded to the SmartATRS relay board in order to test the button sizes on the Recon Jet. The OpenURI application was updated to include the URL of the new interface. An optimum button size was obtained, which resulted in the interface being developed as shown in Figure 35.

Figure 35: SmartATRS GUI for Recon Jet

The entire interface could be seen on the display, however, the Seat In button could be selected and it was not possible to navigate between buttons. As the touchpad needed to be used for navigation, it was established from Recon Instruments that movement on the touchpad produced the American Standard Code for Information Interchange (ACSII) codes for the arrow keys. A JavaScript function was created that monitored the *keypress* events (touchpad movements) on the interface and executed as soon as the interface was loaded (by using the '*window.onload*' method). This function determines the button that received focus by using an If-Else statement for each button that determined which other button to select based on the direction of movement on the touchpad. An extract of the code was shown in Figure 36.

```
window.onload = function () {
    document.getElementById('seatIn').focus();
    focussedButton = 11;
    document.onkeydown = function (e) {
        var evtobj = window.event ? event : e
        var code = evtobj.charCode ? evtobj.charCode : evtobj.keyCode

        //SEATIN
        if (code == 37 && focussedButton == 11) {  //left
            document.getElementById('seatOut').focus();
            focussedButton = 12;
        }
        else if (code == 38 && focussedButton == 11) { //up
            document.getElementById('stop').focus();
            focussedButton = 41;
        }
        else if (code == 39 && focussedButton == 11) { //right
            document.getElementById('seatOut').focus();
            focussedButton = 12;
        }
        else if (code == 40 && focussedButton == 11) { //down
            document.getElementById('tailgateClose').focus();
            focussedButton = 21;
        }
```

Figure 36: JavaScript code to enable navigation using the Recon Jet touchpad

The extract shows the code for the 'Seat In' button. The four buttons on the interface were given unique identifiers (*Id*) in terms of their position in the matrix of buttons on the interface, i.e. 'Seat In' had the *Id* of 11, 'Seat Out' was *Id* 12 while 'Tailgate Close' was assigned *Id* 21. If an ASCII code of 37 (left arrow key) was received then the function changed the focussed button to 'Seat Out'; an ASCII code of 38 (up arrow key) resulted in the focus to change to the 'Emergency Stop' button; a code of 39 (right arrow key) also moved the focus to the 'Seat Out' button, as there were only two buttons in a row; and finally, ASCII 40 (down arrow key) updated the focus to the 'Tailgate Close' button. The JavaScript code for the other buttons followed the same structure, whereby the focus was changed to the surrounding buttons depending on the ASCII codes received.

The code was tested on the Recon Jet and following amendments to the JavaScript code (due to incorrect buttons being focussed), successful navigation between the buttons was achieved. Therefore, Feasibility Trial 5 ascertained that SmartATRS could be used on the Recon Jet, however due to the small display, it was difficult to read the button names compared to a smartphone screen. This trial concluded the series of feasibility trials for research.

5.7 Summary

Five feasibility trials identified technologies that could be incorporated into a framework and potentially tested in the controlled usability evaluations. Trial 1 investigated EEG by using a 64-channel actiCAP to determine the actions that could be reliably detected. However, due to the practicalities of the technology for people with reduced physical ability, it was not included as a controlled usability evaluation. The facial feature tracking algorithm of TLD 1.0 was the subject of trial two that evaluated the accuracy to track the head on a Windows computer. The trial also assessed precision of the algorithm to track objects in video streams and concluded that it was a feasible approach for a computer but due to requiring the MATLAB environment, it could not be supported on a smartphone platform. As the algorithm had since been updated to TLD 2.0 providing greater flexibility as a Windows executable application, this version was analysed in trial three. The trial demonstrated that the time taken to resume tracking after a target re-entered the field of view was reduced compared to TLD 1.0. However, due to the author having insufficient C++ programming knowledge, it was not possible to develop a smartphone implementation of TLD 2.0. Feasibility Trial 4 established whether iOS Switch Control could provide a means to operate a smartphone or tablet with head movements. Item and Point Mode were evaluated and it was concluded that even though both modes enabled successful navigation through the SmartATRS interface, with Point Mode being recommended as it required the least number of head movements in order to select buttons. The final feasibility trial used a Recon Jet smartglass to determine whether it could provide an alternative interaction method to a smartphone or tablet. In order for the device to be used to control SmartATRS, an additional interface was developed that could be visible on the small display of the Recon Jet. By creating specific JavaScript code to change the button focus depending on the movements on the touchpad, the Recon Jet could successfully be used, albeit with the buttons on the display being difficult to read.

The results of the feasibility trials inform the technology and interaction medium aspects of a framework in terms of the modalities that could potentially be included. To ascertain which of these should be considered, controlled usability evaluations involving the user community of people with reduced physical ability were performed. This consisted of integrating iOS Switch Control and a Recon Jet into the concept demonstrator for the research described in Chapter 6.

Chapter 6 Design of Architecture

6.1 Introduction

This chapter describes the characterisation of a SmartPowerchair concept demonstrator as a System of Systems (SoS). An overview of one constituent system (the SmartATRS case study) is provided that contains the defined requirements, system architecture and the user interface design. The characterisation and description of the SoS applies techniques to define the components and capabilities (Henshaw 2013). The Two-dimensional SoS Model based on System of Interest (SoI) (Kinder et al. 2012) is also applied to further describe the constituent systems and potential routes to exploitation. An ongoing Bournemouth University initiative in the form of a SoS risk assessment framework is also described that was applied to the concept demonstrator to identify potential threats and vulnerabilities within the SoS. The concept demonstrator is utilised for the controlled usability evaluations described in Chapter 7.

6.2 SmartATRS Case Study

The smartphone system, SmartATRS, was a developed to replace the ATRS keyfobs (similar to those used to operate automated gates). It was identified, through demonstrations of ATRS to users with reduced physical abilities at the 2011 Mobility Roadshow, that the keyfobs presented a deterrent to potential users due to the poor usability of small buttons and the ability to drop the keyfobs easily, potentially falling out of reach of a powerchair user. This was also emphasised through the author's personal experience of operating ATRS. SmartATRS was originally implemented as two sub-systems; Vehicle and Home Control, each consisting of a separate GUI. The Vehicle Control subsystem operated the ATRS function whereas Home Control could operate any device that could be controlled using a relay[5]. For the purposes of the controlled usability evaluations, only the Vehicle Control subsystem was used.

Based on the demonstrations at the Mobility Roadshow, requirements were defined for SmartATRS using Volere Requirements Shells and categorised in terms of Functionality (FR), Interoperability (IR), Maintainability (MR), Performance (PR), Portability (PTR), Reliability (RR), Safety (SFR) and Usability (UR). The defined requirements were as follows:

1. **SFR1:** SmartATRS shall not prevent ATRS from being operated by the handheld pendants or keyfobs.

[5] E.g. an automatic door opener.

2. **FR1:** SmartATRS shall be able to control the following functions: The Freedom Seat, Tracker Lift, Automated Tailgate and home items.

3. **SFR2:** SmartATRS shall ensure safe operation of all ATRS functions.

4. **SFR3:** SmartATRS shall ensure safe operation of all home control functions.

5. **UR1:** The user interface of SmartATRS shall be created in a design that a user with reduced finger dexterity would be able to use.

6. **RR1:** SmartATRS shall be reliable, as a user would depend on the system for their independence.

7. **FR2:** ATRS shall still function as if being operated by the handheld pendants and keyfobs.

8. **PR1:** SmartATRS shall minimise any additional delay to the functioning of ATRS.

9. **MR1:** SmartATRS shall be easy to configure by installers.

10. **MR2:** SmartATRS shall be easy to install into a standard ATRS.

11. **IR1:** When both ATRS and home items are being controlled by SmartATRS, the smartphone shall bridge between the vehicle LAN and the home LAN automatically and seamlessly.

12. **PTR1:** SmartATRS shall be compatible with all popular smartphone operating systems that have web browsers and customizable voice control.

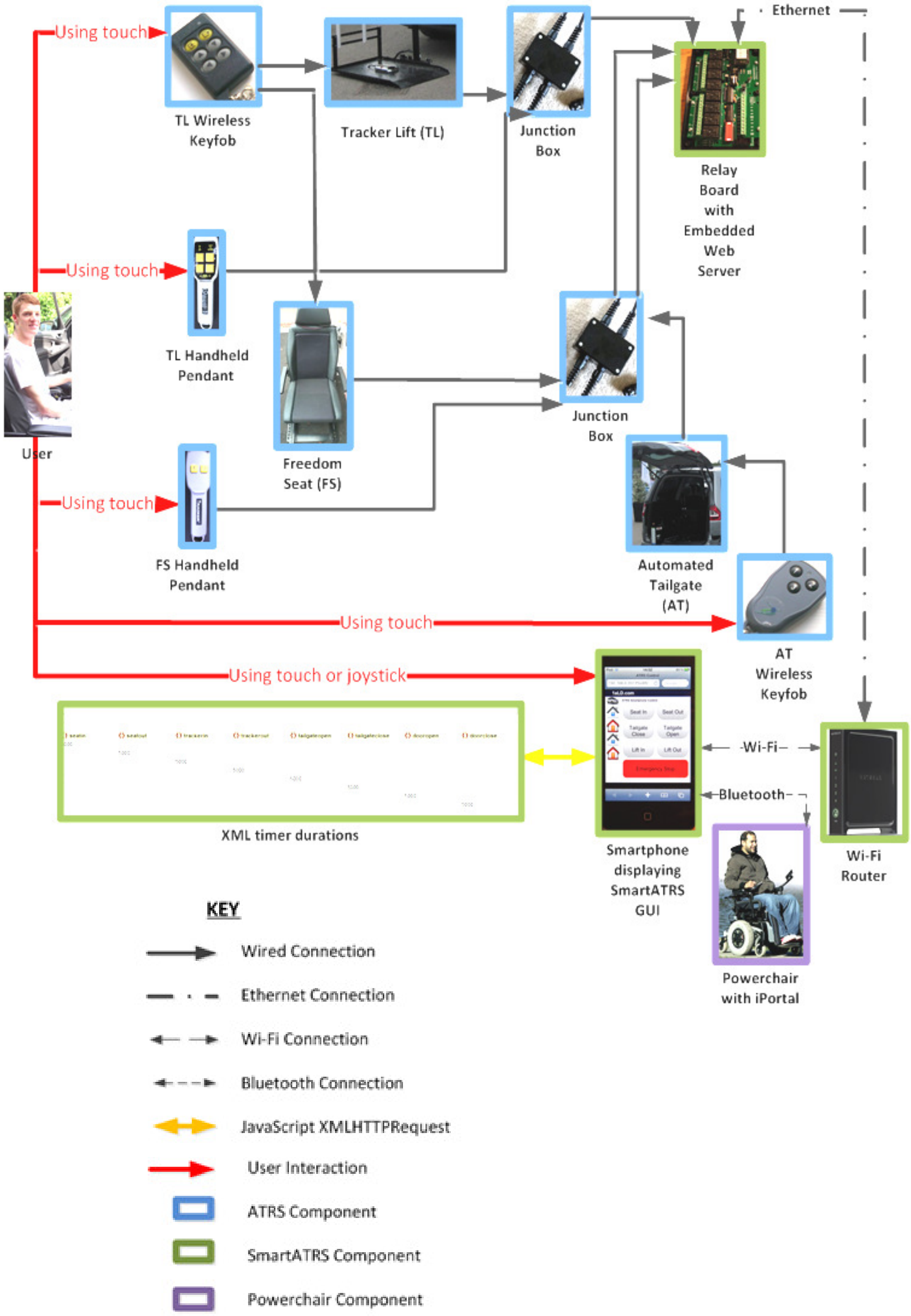

Figure 37: SmartATRS System Architecture diagram

Figure 37 shows the system architecture diagram for SmartATRS. The system was originally developed with two interaction methods (touch and joystick) and integrated with the existing ATRS components. The component interactions are shown by the black and yellow lines and the user interactions are shown in red. In the standard ATRS, keyfobs and handheld pendants were the only interaction methods, whereas with SmartATRS, the original interaction methods are touch or joystick-based. Junction boxes were manufactured to retain the operation of the existing handheld pendants as a backup method. As all of the ATRS components contained relays, a relay board comprising an embedded web server was used to interface between the components and JavaScript. The server stored the HTML and JavaScript GUIs as web pages and JavaScript XMLHttpRequests (objects that transfer data between a web browser and server (Mozilla Developer Network 2017) were transmitted to access an eXtensible Markup Language (XML) file. The file contained the timer durations for each ATRS function and were the integers that represented the number of milliseconds that each function was switched on for. An XML editor was used to view and change the timer durations, therefore ensuring that the process was not visible to end-users. The web server was connected to a Wi-Fi router located in the vehicle using Ethernet. The router created a secure Wi-Fi Protected Access II (WPA2) network whereby smartphones or other Wi-Fi enabled devices could connect to the GUI by entering the URL or accessing a bookmark. The two interaction methods of SmartATRS are touch and joystick-based. Joystick control utilises iPortal (Dynamic Controls 2016) to communicate with a device via Bluetooth. This enables the powerchair joystick to be used for navigation around the device and hence the SmartATRS user interface. The usability of SmartATRS is improved by the securing of the device to the arm of the powerchair via an 'off-the-shelf' mount.

A human-centred design approach was adopted for the user interface (shown in Figure 38), which was designed based upon the views obtained from the people with reduced physical ability at the 2011 Mobility Roadshow. The user interface incorporated user feedback and safety features that were not present in the keyfobs. The ATRS functions are activated through seven large command buttons (Figure 11) with enhanced user feedback and safety features compared to the keyfobs. This includes automatic timings of functions and safety interlocks between functions. An example of one interlock is between the tailgate and the lift where the tailgate is disabled from operating when the lift is not fully stowed in the vehicle, therefore, preventing the user from closing the tailgate onto the lift (which is possible in standard ATRS) and causes potential damage. The other safety feature is an emergency stop function accessed by a large red button that is twice the size of the other buttons on the interface. This feature terminates all currently operating functions immediately, which is a significant advantage over the keyfobs where functions are only terminated individually. Improved user feedback is provided by the background colours of the command buttons changing according to the current state of ATRS. When a function operates, the background colour changes to light blue and only reverts to the original colour when the function completes. The exceptions to this are the 'Close Tailgate' and 'Lift Out' buttons that change to orange and disable when necessary due to the safety interlocks.

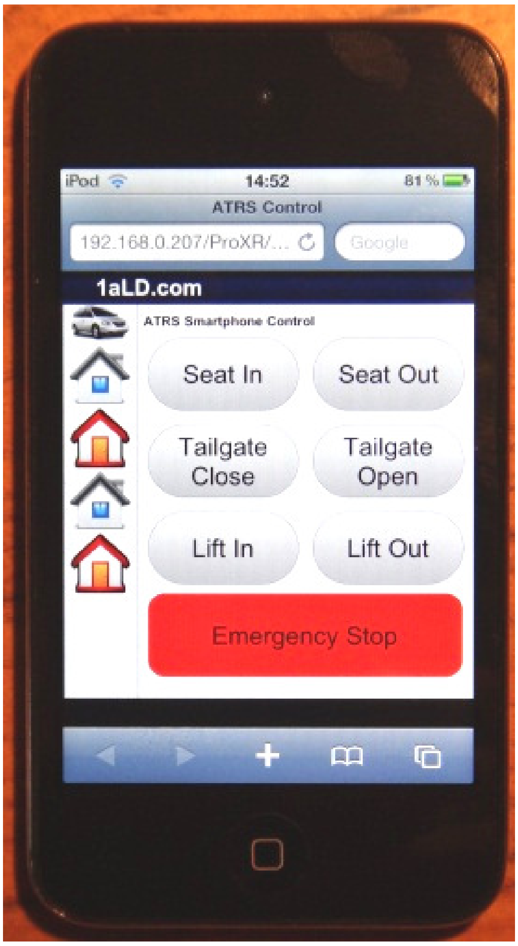

Figure 38: SmartATRS user interface

Following the author's personal experience of using SmartATRS for the daily transportation of a powerchair, the system provides a basis for a concept demonstrator (known as the SmartPowerchair) where additional interaction methods can be incorporated into the system for evaluation by the user community. SmartATRS relied on the interoperability between components that could be seen as constituent systems of the SmartPowerchair SoS. Analysis was therefore conducted into characterisation and description using System of Interest (SoI) to assist with the formation of the evaluations.

6.3 SmartPowerchair as a System of Systems

The SmartPowerchair is a SoS constructed from a number of different sub-systems, components and interactions. Analysis of the SmartPowerchair, as a SoS, is described by Whittington et al. (2015c), referenced in Appendix D. SmartATRS is one constituent system of the SmartPowerchair SoS that controls the ATRS components to support the interaction between a powerchair and vehicle. Any technologies that are incorporated into the SoS to form additional interaction methods, are seen as further constituent systems. By using the characterisation and description of SoS suggested in the T-AREA-SoS (Henshaw 2013), the relationships between the SmartPowerchair components and their capabilities are illustrated in

Table 8.

Table 8: Characterisation of the SmartPowerchair SoS

SoS Components	Capabilities		Function Services
	Purpose	*Examples of use*	
Smartphone	- To interact with SmartATRS. - To communicate with users.	- Control the seat, lift and tailgate. - Perform an emergency stop.	- Display GUI. - Execute JavaScript. - Communicate with wireless router.
Tablet	- To interact with SmartATRS. - To communicate with users.	- Control the seat, lift and tailgate. - Perform an emergency stop.	- Display GUI. - Execute JavaScript. - Communicate with wireless router.
Smartglass	- To interact with SmartATRS. - To communicate with users.	- Control the seat, lift and tailgate. - Perform an emergency stop.	- Display GUI. - Execute JavaScript. - Communicate with wireless router.

SoS Components	Capabilities		Function Services
	Purpose	*Examples of use*	
Powerchair	- To transport users.	- Provide access to the vehicle in an outdoor environment.	- Connect with joystick controller. - Receive commands from joystick controller.
Joystick controller	- To control powerchair navigation and secondary functions.	- Allow the powerchair to be driven. - Allow communication with iPortal.	- Drive powerchair. - Operate lights and horn. - Display malfunctions and battery charge status.
iPortal	- To communicate with smartphone/tablet via Bluetooth.	- Trigger functions on smartphone/tablet.	- Control smartphone/tablet operating system. - Navigate web pages.
Automated Transport and Retrieval System	- To aid transition between the vehicle and powerchair.	- Remotely navigate powerchair to rear of vehicle. - Autonomously dock powerchair on to lift in rear of vehicle.	- Connect to LIDAR unit. - Control powerchair using LIDAR and sensor data.
SmartATRS	- To interface with relay board via JavaScript.	- Used to operate seat, lift and tailgate. - Used to perform ATRS emergency stops.	- Control timeouts and interlocks. - Provide status feedback to users.
Relay board	- To receive commands from JavaScript.	- Used to control SmartATRS.	- Switch seat, lift and tailgate relays on/off as appropriate. - Communicate with wireless router.
Seat	- To follow a predefined path to enter/exit the vehicle.	- Used to transport users in/out of the vehicle.	- Enable a safe transfer to powerchair - Stop at a predefined distance from ground.
Lift	- To enter/exit the vehicle.	- Used to transport powerchair in/out of the vehicle.	- Enable the powerchair to be lifted in/out of the vehicle. - Stop when ground sensor is activated.
Tailgate	- To open/close.	- Used to enable lift to enter/exit the vehicle.	- Driven by a pneumatic ram. - Stop when fully opened/closed.

The main components of the SoS are the powerchair, integrated technologies (smartphone, tablet and smartglass), relay board and ATRS. The relay board forms the interface between ATRS and SmartATRS, by connecting each relay to an ATRS component (seat, lift and tailgate). By utilising iPortal to communicate between the powerchair and smartphone via Bluetooth, joystick control was developed as an alternative interaction method to touch.

The SmartPowerchair SoS can be further described using the SoI framework by adapting the Two-dimensional SoS Model based on the Capability Cube model developed by the defence industry (Harding et al. 2009), as shown in Figure 39. This model illustrates the lifecycle of a SoS from concept to retirement, with the levels: Concept and Technology Development, Component, Systems, System of Systems Engineering and Capability.

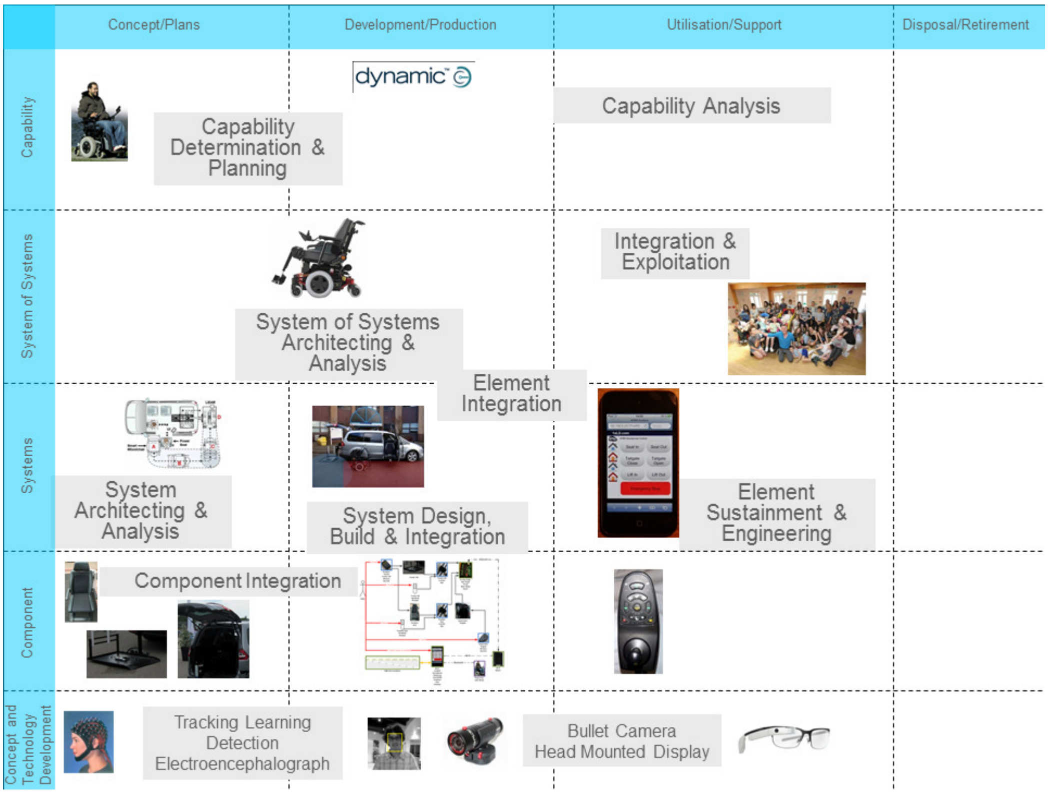

Figure 39: Two-dimensional SoS Model of SmartPowerchair

The Capability level includes collaborations with stakeholders in the mobility industry (e.g. Dynamic Controls), to establish requirements for the capabilities and functionality of the technologies to be incorporated into SmartPowerchair concept demonstrator and hence a supporting framework. The Utilisation/Support phase involves exploiting the completed framework to the user community, the assistive technology and healthcare domains to assess the suitability of the framework to recommend technologies based on the abilities of users. Concept and Technology Development will be performed on the SmartPowerchair by integrating new pervasive technologies, which could result in the expansion of a framework if the technologies are deemed to be suitable for people with reduced physical ability.

Through analysis of the SmartPowerchair as a SoS through characterisation, description and SoI, a detailed comprehension of the components and interactions was obtained and the Two-dimensional SoS model established the exploitation stages of the completed framework. Based on this understanding, three controlled usability evaluations were conducted to assess interaction methods through application of additional technology to the SmartPowerchair concept demonstrator (described in Chapter 7).

6.4 Interoperability of SoS

An example of interoperability within the SmartPowerchair SoS was the integration of a rear view camera into a standard powerchair to assist the user with manoeuvring in confined spaces. This was a common challenge that was revealed by the requirements elicitation phase.

A rear view camera (Rear View Safety Inc. 2017a) was installed that was a commercially-available product, designed for installation in vehicles as a backup camera system by being water, dust and shock-proof. The existing mounting bracket was used to install the camera onto the rear of the powerchair in a location that would not be susceptible to damage. The camera operated over Wi-Fi and a live image could be displayed on a mobile device using the GoVue application (Rear View Safety Inc. 2017b). The camera system enabled viewing of a live stream from the camera, recording video and capturing still images. The product included a Wi-Fi transmitter so that there was no requirement for a Wi-Fi or internet connection in order to use the camera.

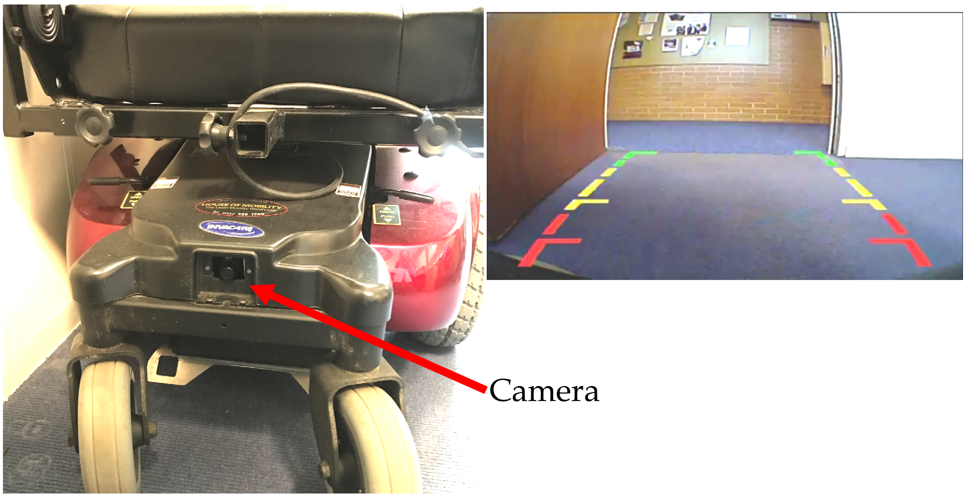

Figure 40: The camera mounted to the powerchair and the rear view to assist with doorway navigation

Once the camera was mounted to the powerchair the rear view could successfully be viewed on a smartphone (as shown in Figure 40), and was tested by reversing the powerchair through a doorway using the camera for navigation. The proximity indicators assist with judging the width of the doorway to ensure that the powerchair does not collide. The solution was demonstrated at the 2016 Mobility Roadshow and all visitors in powerchairs expressed an interest by commenting that it would be a solution that they would consider. This presents an example of a product being utilised as an assistive technology that was not specifically designed for this purpose. The success of the solution was due to the interoperability between the camera, Wi-Fi transmitter, smartphone and powerchair. Based on the author’s experience of the greater visibility provided by the rear view camera, which was reiterated by the visitors at the Mobility Roadshow, it was concluded that the solution was successful to assist with navigation. Further examples of interoperability are contained within the feasibility trials described in Chapter 5.

6.5 Risk Assessment of SoS (RASoS) Initiative

The SmartPowerchair concept demonstrator was applied to an ongoing Bournemouth University initiative based on a student project known as the RASoS (Risk Assessment for Systems of Systems) framework. The framework has not been validated through domain experts and applied to other case studies.

The RASoS was based on the Sp800-30 developed by the National Institute of Standards and Technology (NIST). This risk assessment standard provides guidelines for the development of an effective risk management program, containing both the definitions and the practical guidance necessary for assessing and mitigating risks identified within IT systems (Stoneburner et al. 2002). Risk assessment under Sp800-30 involves nine steps which fall under three distinct stages. Each of the nine steps gives a defined output that is obtained after the system analysis. The nine stages of NIST Sp800-30 and their output is summarised in Table 9.

Table 9: The nine steps of Sp800

Steps	Defined Output
Identification	
Step 1: System Characterisation	Characterisation of the IT system assessed, a good picture of the IT system environment, and delineation of system boundary
Step 2: Threat Identification	A threat statement containing a list of threat-sources that could exploit system vulnerabilities
Step 3: Vulnerability Identification	A list of the system vulnerabilities that could be exercised by the potential threat-sources
Step 4: Control Analysis	List of current or planned controls used for the IT system to mitigate the likelihood of a vulnerability's being exercised and reduce the impact of such an adverse event
Analysis	
Step 5: Likelihood Determination	Likelihood rating (High, Medium, Low)
Step 6: Impact Analysis	Magnitude of impact (High, Medium, or Low)
Step 7: Risk Determination	Risk level (High, Medium, Low)
Mitigation	
Step 8: Control Recommendations	Recommendation of control(s) and alternative solutions to mitigate risk
Step 9: Results Documentation	Risk assessment report that describes the threats and vulnerabilities, measures the risk, and provides recommendations for control implementation

The framework examples presented above underestimates the identification of risks centred on the human involvement in the system. Therefore, the analysis of the profile of the human and their relationship with the system requires close attention especially in assistive environments. Furthermore, the interoperability across different SoS, constituent systems and their components can have an impact of the characterisation of the system, which can consequently influence risk analysis. It is also difficult to capture risks centred on emergent behaviour of SoS with the step or stages of existing risk assessment approaches.

The RASoS framework used the three main risk assessment processes; (1) risk identification, (2) risk analysis and (3) risk evaluation. The key changes and additions of the new steps based on its application to the concept demonstrator are as follows.

6.5.1 Risk Identification

This is the first stage of the risk assessment to gain an in-depth understanding of the system structure, whilst identifying threat-source and vulnerable system elements. The ultimate goal of this stage is to identify the risks that are present within the SoS environment. To successfully achieve this, various steps are necessary, which are summarised in Table 10.

Table 10: Risk identification steps

#	Step	Description
1	Human System Interaction (HSI)	Identification of human involvement in the system. Analysis of human profiles and their relationship with the system.
2	Threat-Source Identification	Identification of primary threat-source that could potentially induce risks.
3	Vulnerabilities Identification	Identification of system elements that could be exploited by the threat-source.
4	Risk Identification	Identification of risks that are a result of system vulnerabilities being exploited by threat-source.

The first step is designed for the analysis of any human elements that may be involved within the SoS. This involves the completion of a 'Human System Interaction' (HSI) analysis form focusing on roles, responsibilities, relationships and ownership, using a template. The template can be completed by the system owner or the person carrying out the risk assessment. This step is not mandatory and may not be applicable if there is no human involvement. However, the completion of this step is highly recommended if there is any form of human interaction with the constituent systems or the pervasive technologies.

The proposed RASoS framework uses an adaptation of abstraction stacks to complete step 2 (Threat-source identification) and step 3 (Vulnerabilities identification). An Abstraction Stack represents a single system inside one frame, where all the system elements are organised in the order of system structure. In contrast to this, the adopted abstraction stack uses a mainframe for representing a SoS environment, consisting of further sub-frames which represent the individual systems within the SoS.

The goal of steps 2 and 3 is to identify the threat-source and the system vulnerabilities that can be exploited by the threat source. Stoneburner et al. (2002) state that the threat source is "a situation and method that may accidentally trigger a vulnerability", where a vulnerability is described as a "weakness that can be accidently triggered or intentionally exploited". Given the nature of SoS and the system structure, a constituent system can be classified as a threat-source, as they operate the system elements which could potentially trigger system functions leading to exploitation of 'weaknesses'. Therefore, all of the system elements are classed as vulnerabilities of the system. Furthermore, interoperability, which is another major feature of SoS, enables the interaction between individual systems. This could lead to one or more system exploiting another system and vice versa. Thus, all constituent systems are deduced as vulnerabilities of a SoS. Putting this into the context of Abstraction Stacks, all of the sub-frames are classified as threat-source and system elements as vulnerabilities. In addition to this, any sub-frame that interacts with another sub-frame is classed as a vulnerability of the overall system. Table 11 is an example of an extract from the risk identification stage of the SmartPowerchair.

Table 11: An extract from the threat-source, vulnerabilities and risk identification

ID	Vulnerabilities	Risk
Threat-Source: System 1 (Smartphone)		
S1	System element 2 (Wi-Fi)	Smartphone must be in range of the router

		for Wi-Fi to be accessible.
S2	System 2 (Vehicle)	Vehicle cannot receive commands if the smartphone is not available.

6.5.2 Risk Analysis

The second stage of the risk assessment is analysis to determine the consequences of the risks that are highlighted during the identification stage. This stage consists of five further steps to evaluate the consequences of the risks on the SoS. The steps involved in this stage are summarised in Table 11.

Table 12: Risks analysis steps

#	Step	Description
5	Likelihood Analysis	Analysis of the frequency and probability of the risk occurring.
6	Impact on the System	Qualitative assessment of the effect of the risk on the system.
7	Interoperability Analysis	The effect of the risk on the interoperability of SoS.
8	Impact Level Analysis	Determination of the impact level of the risk depending upon the impact on the system.
9	Risk Level Analysis	Scale of the risk measured against the likelihood and the impact level of the risk.

It is necessary to discuss some of the less self-explanatory steps in more detail. For example, step 6 that focuses on impact on the system, is purely a qualitative assessment made by the system owners or the system users. This step determines the effect of the risks that are identified during step 4. For every risk, the system owner or the system user evaluates the impact of the risk on the system. Four essential impact factors must be considered while undertaking the impact analysis: (1) the impact on the system element; (2) the impact on individual systems; (3) the impact on the SoS; and also (4) the impact on HSI. The results should be a summary of the four impact factors documented appropriately. An additional step introduced in RASoS is interoperability analysis (step 7). This is also a purely qualitative assessment based upon the expertise of the system engineers and risk assessors. The impact on the interoperability of the SoS must be assessed against every risk that has been identified. Not all risks will necessarily have an impact on interoperability; some will have lesser impacts. These should all be taken into consideration and the results should be documented appropriately for further evaluation during step 8, which determines a score for impact level.

Table 13 shows an extract of risks analysis based on the risk identification results from Table 11.

Table 13: Example of Risk Analysis

ID	Identified risk	Likelihood (L,M,H)	Impact on systems	Impact on interoperability	Impact Level (L,M,H)	Risk Level (L,M,H)
S1	Smartphone must be in range of the router for Wi-Fi to be accessible	L	Wi-Fi connection will not be available for smartphone. The	The smartphone will not be able to connect and communicate with other systems.	H	M

	.		system cannot be used.			
S2	Vehicle cannot receive commands if the smartphone is not available.	M	The system cannot be operated without the smartphone.	System cannot operate.	H	H

6.5.3 Risk Evaluation

This is the final stage of the risk assessment and evaluates the overall impact of the risk and plan control measures against those risks to bring them to an acceptable level. To achieve this, the stage consists of two further steps as shown in Table 14.

Table 14: Risk evaluation steps

#	Step	Description
10	Emergent Behaviour and Control Measures	Analysis of emergent behaviour and planning control measures against them to bring a risk to an acceptable level.
11	Documentation	Documenting the steps and the outcomes of risk assessment.

The purpose of this step is to identify any 'unacceptable' risks and potential emergent behaviours to plan appropriate measures against them. The goal of control measures is to reduce the risk of any system to an acceptable level (Stoneburner et al. 2002) with any risks that have a 'High' risk level being given top priority and responsive actions taken as soon as possible. Some systems may be used in a different context due to the emergent behaviour of the users and systems, which may impact the utilisation of the overall SoS. Table 15 provides an extract from this step i.e. the emergent behaviour analysis and control measures.

Table 15: Emergent behaviour analysis and control measures

ID	Risk Level (L,M,H)	Measures
SA6	H	People with glasses may have to be advised to use contact lenses to be able to use smartglasses. If this is not possible, then other means should be used for interacting with the SmartATRS, e.g. smartphones.
P2	H	The app could be made compatible with the smartphones. A back-up can be stored in smartphones, or downloaded using Wi-Fi or mobile data.
P1, SA4, S3	M	Usage of mobile data such as 3g or 4g should be alternatives.

An example provided in Table 15 is the unpredictable behaviour of the user, i.e. using smartglasses, e.g. a Recon Jet (Recon Instruments 2017), to interact with the systems while wearing glasses. Another example is the usage of 3g or 4g when Wi-Fi is not available and the flexibility of the system enabling such interactions. These examples are outputs of RASoS framework as applied to the SmartPowerchair concept demonstrator that utilises Wi-Fi connection and different input modalities and systems (e.g. touch, voice and keyfobs) to enable the interaction between the SmartPowerchair and a vehicle.

The RASoS is at its initial developmental stages but provided a holistic view of the SoS from which threat-sources and vulnerabilities can be identified. In addition, a template for HSI was designed to capture any human involvement with the system. RASoS is not a key contribution of the research as it was designed by Kewal Rai (2016) and applied to the concept demonstrator as an example of use.

6.6 Conclusion

The SmartPowerchair concept demonstrator can be described as a SoS containing various constituent systems including the SmartATRS case study and other technologies that can provide alternative interaction methods for people with reduced physical ability, such as head mounted displays and rear view cameras. SmartATRS was originally developed based on the views obtained from the ATRS demonstrations at the 2011 Mobility Roadshow, which were used to derive a set of requirements for the system. A system architecture was subsequently developed incorporating the standard ATRS, a smartphone, relay board with an embedded web server and the existing keyfobs and handheld pendants. The user interface design introduced additional safety features into ATRS such as improved user feedback, safety interlocks and automatic timing of functions. Characterisation of SoS and SoI were subsequently applied to describe the SmartPowerchair SoS and enabled the identification of the individual components, as well as considerations for routes to exploitation. An example of interoperability of SoS was described through the integration of a rear view camera into a standard powerchair to assist with manoeuvring. The concept demonstrator was further applied to the RASoS framework that provides a risk assessment structure for a SoS to identify threat-sources and vulnerabilities within the system elements and environment. Through considering the SmartPowerchair as a SoS, a greater understanding of the individual aspects could be obtained that contributed to the establishment of the conducted controlled usability evaluations described in Chapter 7.

Chapter 7 Research Results (iii) – Controlled Usability Evaluations

7.1 Introduction

This chapter presents the results from the three controlled usability evaluations performed during the research that compared keyfob, touch, joystick and head-based interactions and the use of a smartglass as alternative interaction medium. To assist with the identification of tasks that the participants would perform during the evaluations to operate SmartATRS, the system is further described using Hierarchical Task Analysis (HTA). The first evaluation utilised the vehicle and the ATRS whereas the subsequent evaluations were performed with a simulation of SmartATRS. The System Usability Scale (SUS) and NASA Task Load Index (TLX) results enabled a comparison of the modalities of interaction.

7.2 SmartATRS Hierarchical Task Analysis

Hierarchical Task Analysis (HTA) was used to obtain an understanding of the tasks involved to operate SmartATRS, thereby determining the tasks to be completed in the controlled usability evaluations. The HTA defined the tasks in their hierarchical structure by deconstructing the high-level parent task (i.e. departing or arriving in a vehicle) into sub-tasks by using a numbering system.

The SmartATRS HTA for departing in the vehicle is shown in Appendix H. Departing in a SmartATRS equipped vehicle consists of six sub tasks: 1) preparing vehicle, 2) activating lift and seat out of vehicle, 3) preparing powerchair, 4) autonomous docking, 5) activating lift and seat into vehicle and 6) departure. These tasks need to be performed sequentially in order to successfully depart the vehicle with the powerchair and driver safely stowed. The addition of screenshots of SmartATRS to the HTA highlighted the tasks currently supported by smartphone interaction.

Task 1 involves positioning the powerchair near to the driver's door by moving the joystick in the required direction. This allows the driver to reach the door, so that the seat can be driven out in Task 2. The lift and seat are activated in Task 2, using iPortal to control a smartphone via the powerchair joystick. After iPortal has been engaged using the buttons on the joystick control, it is necessary to tap the joystick in order to reach the 'Seat Out' button the SmartATRS user interface. The 'Lift Out' button is activated via the same method using the joystick. Whist the lift and seat are being driven out of the vehicle, the driver progresses to Task 3 to prepare the powerchair for autonomous docking. This involves five further tasks: switching on the LIDAR unit which is utilised for the docking, raising the footrest to enable the powerchair to fit onto the lift, the driver transferring to the seat and folding the seat back using the joystick to ensure that the powerchair is low enough to fit into the vehicle. Task 4 uses ATRS to activate the remote control feature using the Joystick Control Module attached to the side of the driver's seat. The driver then remotely navigates the powerchair to the rear of the vehicle using the joystick on the module. Once the powerchair is in line of sight of the fiducials attached to the lift, autonomous docking is activated using the button on the module. Following the docking, the lift and seat are stowed into the vehicle in Task 5 using the SmartATRS user interface via touch-based interaction. The final task consists of departing in the vehicle by closing the driver's door, fastening the seat belt, adjusting the steering wheel into the driver's preferred position and starting the ignition. The HTA for arriving in a SmartATRS equipped vehicle would consist of an identical set of tasks in the reverse order.

Creating the HTA allowed the parent tasks to be deconstructed with the subtasks forming the basis for the controlled usability evaluation tasks and the instructions to be provided to the participants to ensure the safe interaction with SmartATRS. This allowed a greater understanding of the processes within SmartATRS to be determined.

7.3 Evaluation 1 (Keyfob, Touch and Joystick-based Interactions)

The first controlled usability evaluation was conducted to assess the usability of the interaction methods: keyfobs, touch and joystick. The evaluation also provided a means to verify the GUI design of SmartATRS to ensure that it was "fit for purpose". Information regarding participant profile, the evaluation procedure and the results are described as follows.

Participants: The evaluation was performed by 12 participants (8 males and 4 females between the ages of 20 and 60) from a cross-section of working backgrounds within a UK university including; students, administrators and academics. The participants were able-bodied, but had experience of working with people who have reduced physical ability.

Procedure: The evaluation was held in a car park using an ATRS-equipped vehicle. The location was specifically chosen as it was a relatively quiet area of the campus. The risk assessment for the evaluation (presented in Appendix I) highlighted the need for close supervision of participants to prevent potential damage or injury occurring due to incorrect use of ATRS. Allocated timeslots of 15 minutes were provided in advance to each participant. The participants were given a briefing in a classroom prior to conducting the task. The briefing consisted of an introduction to ATRS and SmartATRS, the purpose of the evaluation and the expectations of the participants. There was an opportunity for questions to be asked.

The participants performed a series of six tasks using keyfob, touch-based and joystick interactions, before completing a questionnaire pack (provided in Appendix J) concerning the usability of the methods. The first section of the pack contained ten statements adapted from SUS, where participants rated ten statements on a five-point scale of strength of agreement from 'Strongly Disagree' to 'Strongly Agree'. Typical statements included: i) 'I thought using the keyfobs were easy', ii) 'I thought that the Emergency Stop feature of SmartATRS by touch was safe' and iii) 'I would imagine that most people would learn to use SmartATRS by joystick very quickly'.

The second section of the pack contained questions about the workload experienced during the tasks, based on NASA TLX. The workload types measured were: Physical Demand, Mental Demand, Temporal Demand, Performance, Effort and Frustration, where participants rated the workload required on scales from Very Low to Very High. Example questions included: i) How mentally demanding was using the keyfobs, ii) How physically demanding was using SmartATRS by touch and iii) How hurried or rushed was the Emergency Stop task using SmartATRS by joystick. During the evaluation, the participants performed the following six predefined tasks:

1. Driving the seat out of the vehicle.
2. Opening the tailgate of the vehicle.
3. Driving the lift out of the vehicle.
4. Performing an Emergency Stop whilst the seat and lift are driving into the vehicle simultaneously.
5. Closing the tailgate of the vehicle.

6. Driving the seat in and out of the vehicle.

Tasks 1, 2, 3, 5 and 6 were specifically chosen because they have to be performed whilst using SmartATRS and Task 5 was included to evaluate the safety. There were no other tasks that could be performed with SmartATRS. In the emergency stop task, the command “Stop Lift!” was given during the simultaneous operation of the lift and seat and the participant had to stop the lift immediately. The participant was aware that an emergency stop had to be performed, but were unaware of whether it would be to stop the lift or seat. A stopwatch was used to measure the time between the command being given and the lift stopping.

Tasks 1 to 5 were performed using two interaction methods: keyfobs and touch. Task 6 was only performed using the joystick to illustrate it as an interaction method. Step-by-step instructions were given to the participants for each task as they were all new to ATRS.

Results: An analysis of the responses from each questionnaire was then performed and used to describe the findings.

SUS: Analysis using the Adjective Rating Scale revealed that keyfob interaction achieved a score of 50.5 (‘Poor Usability’), whereas touch-based achieved 81.3 (‘Good Usability’) and interaction using the joystick achieved 63.8 (‘OK Usability’). This clearly highlighted that touch interaction was the most usable; with most participants finding keyfob-based interaction challenging.

One of the most important results highlighted the safety of the Emergency Stop function, was found when 100% of participants agreed that it was safe using SmartATRS, compared with only 33% using the keyfobs. This result was supported by the results from emergency stop times for the keyfobs and touch-based interaction.

Participants commented that when using the keyfobs, it was necessary to make a decision as to which button to press to stop the lift, whereas with touch-based interaction, the Emergency Stop button could be pressed to immediately stop all functions. The standard deviation for the keyfobs was 6.8 seconds, compared to only 1.2 seconds for touch-based interaction.

NASA TLX: The box plots in Figure 41-46 provide a comparison of the workload experienced when using keyfobs, touch and joystick-based interaction. The temporal demand of the joystick has been omitted as the emergency stop task was not performed using the joystick.

The box plots illustrate the differences in the workload experienced between interaction methods and show the minimum, lower quartile, median, upper quartile and maximum values. It can be seen that touch-based had a significantly lower workload level in all workload types than the keyfobs. There are greater mental and physical demands with keyfobs than touch-based interactions. As there is an increased likelihood of not successfully accomplishing the tasks with keyfobs, the temporal demand appears higher, whereas with touch-based there a low temporal demand as there is an improved chance of accomplishing tasks successfully.

A second notable observation was the higher effort and frustration levels of the joystick in comparison with touch-based, likely to be caused by a steeper learning curve. It was also found that touch-based had a greater discrepancy between the maximum values and the majority of the data. There was a minority of users who experienced low workload levels when using the keyfobs, but overall the box plots are fairly conclusive that touch-based interaction is the most efficient and least demanding interaction method.

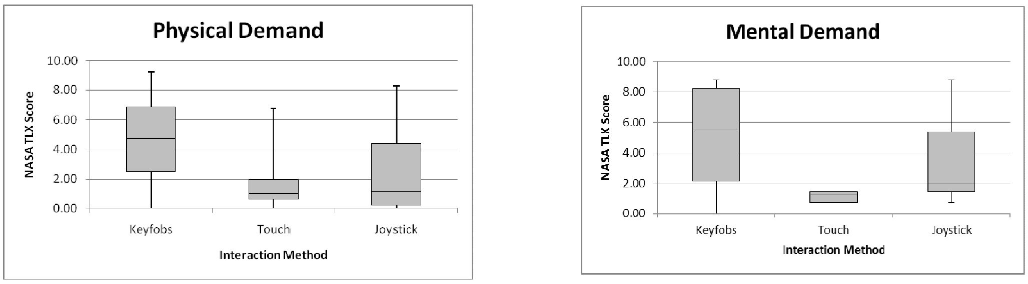

Figure 41: Comparing Mental and Physical Demand experienced

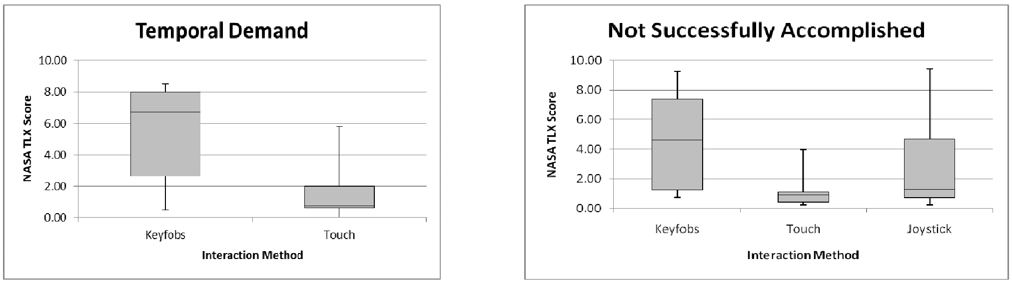

Figure 42: Comparing Temporal Demand experienced and Not Successfully Accomplishing tasks

The second controlled usability evaluation compared touch and head-based interaction methods by integrating iOS Switch Control into the concept demonstrator. The evaluation results are described in the subsequent section.

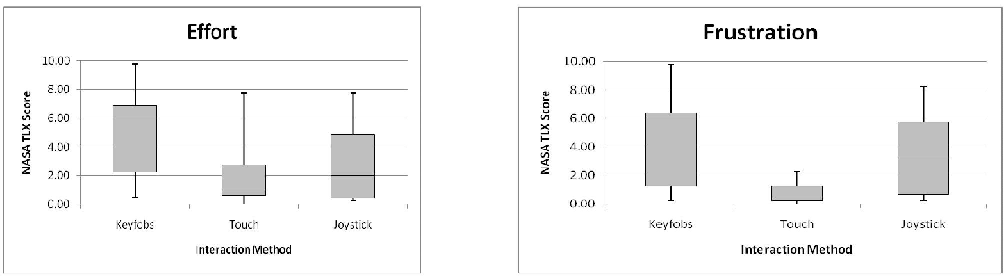

Figure 43: Comparing Effort and Frustration experienced

7.4 Evaluation 2 (Touch and Head-based Interactions)

The second controlled usability evaluation compared touch and head-based interaction methods to ascertain the suitability for people with reduced physical ability. Following the safety implications of unfamiliar users operating SmartATRS in Evaluation 1, the remaining evaluations were performed using a simulation as the system is required by the author on a daily basis. Another advantage of the simulation was that the evaluations could be performed within an indoor environment.

7.4.1 Simulation Development

The SmartATRS simulation consisted of a relay board with an embedded web server (identical to the relay board located in the vehicle), smartphone, Windows laptop and a projector. The web server on the relay board was connected to a Wireless LAN (WLAN) module, so that a smartphone could connect to the relay board wirelessly. The same user interface for SmartATRS existed in the simulation with the relays being operated from the JavaScript, but the relays were not connected to any functions. A Windows laptop also connected to the relay board wirelessly and executed a separate piece of JavaScript code that continuously monitored the state on the relays.

The simulation displayed video clips to represent the currently operating relays that were stored on the laptop as Moving Picture Experts group (MPEG-4) files, as the files are too large to be stored on the webserver. Six video clips were created to represent each ATRS function and were all displayed on a single interface, as shown in Figure 44.

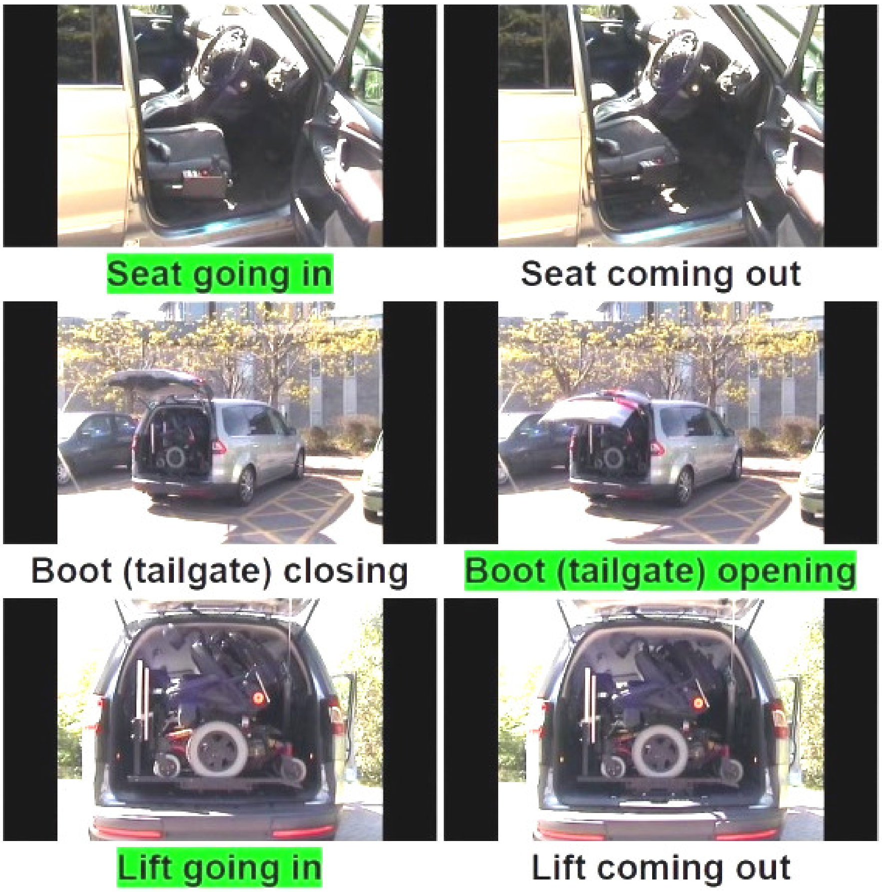

Figure 44: SmartATRS Simulation Interface

When a relay is operated, the appropriate video played and stopped either when the function completed or when the relay was switched off prior to completion. In the latter case, the video was paused and resumed once the relay was switched on. It was not possible for the opposite motion video (i.e. Seat In and Seat Out) to be played simultaneously, as this was impossible in the real system. Therefore, the video will pause the opposite motion video.

A separate user interface was created for the SmartATRS simulation. The JavaScript code was different to the SmartATRS interface as it read the relay statuses and did not control the relays. The same stylesheets were used as in SmartATRS to maintain consistency. Using a *setInterval()* JavaScript method that executed every 500 milliseconds, the current status of the relays were obtained by sending the command *'254,124,1;:,", "", ""'* to the relay board as a *SendMacroCommand*. The board returned an 8 bit binary value between 0 and 255 to indicate the current states of all of the relays. If a single relay was latched-on, the return values were as shown in Table 16.

Table 16: Latched-on returned values

Relay Number	Latched-on Returned Value
1	1
2	2
3	4
4	8
5	16
6	32
7	64
8	128

The values were combined if multiple relays were switched on, e.g. if Relays 1 and 8 were switched on, the board would return a value of 129. After the command was sent, a JavaScript function, *playVideos(),* was called using the *setTimeout* method. The *setTimeout* method allowed for a two-second duration to elapse prior to the *playVideos()* function being executed, to allow time for the relay board to respond.

In the standard interface for the relay board, the retuned value was displayed in a textbox. In the simulation, a JavaScript function was called to extract the contents of the textbox by using a *document.getElementById().innerHTML* method that assigned the value to a variable. The variable was then converted into an integer so that bitwise AND logical operations could be performed to obtain which relays were latched on. The operands used depended on which relay statuses were being obtained and were identical to the returned value of each relay. This ensured that when multiple relays were switched on, the irrelevant bits were filtered out. The operand and latched-on return values are shown in Table 17.

Table 17: Operand values and latched-on returned values

Relay Number	SmartATRS Function	Operand	Latched-on Returned Value
1	Seat In	00000001	1
2	Seat Out	00000010	2
3	Close Tailgate	00000100	4
4	Open Tailgate	00001000	8
5	Lift In	00010000	16
6	Lift Out	00100000	32

For example, the result of the bitwise AND operation would be 4 if the Close Tailgate relay was latched-on and 0 would be returned if the relay was latched-off. The results were stored in global state variables for each function and the overall state of the relays was returned to the *playVideos()* function. Six HTML5 video objects were initiated, one for each SmartATRS function. The objects were linked to the videos stored on the laptop using localhost URLs to access a 'SmartATRS_Simulation' directory on the C: drive. The *playVideos()* function first checked whether the overall relay state had changed since the last execution. If the state had not changed, no further actions were taken, as the playback of the videos did not need to be changed. If the state had changed, 'IF' statements were executed that updated the status of each video. A comparison statement checked whether the states of the functions equalled the latched-on returned value. If the statement returned TRUE, the corresponding opposite motion was paused and the required motion video was reset and played. This ensured that the two opposite motion videos would not be played simultaneously. The advantage developing the simulation as a separate interface was that the standard functionality of SmartATRS interface was not modified. Therefore, there would not be any adverse performance effects, ensuring maximum realism.

Participants: Three organisations were approached to establish a niche user group of 17 participants who were of both genders and who had varying disabilities requiring the use of a powerchair or wheelchair (such as Cerebral Palsy, Duchenne's Muscular Dystrophy and Ataxia Telangiectasia) with either reduced dexterity and/or speech ability. The participants thereby became a representative sample to accurately assess the usability of the interaction methods. As the evaluation was contacted with a user group classed as vulnerable, ethical approval was sought from the University ethics panel prior to conduction.

Procedure: The participants were provided with the documents in Appendix K. Informed consent was obtained from all participants and an information sheet was given to each participant prior to the evaluation. The participants used the tablet to control the SmartATRS simulation by completing the set of tasks defined in Evaluation 1. However, the accuracy of the emergency stop task was improved by using a video camera instead of a stopwatch. The entire task was recorded and the stopping times for each participant were elicited by analysis using video editing software and calculating the exact duration elapsed between the command being spoken and the function terminating. The usability of the interaction methods were assessed by observing whether the video clip playing on the laptop corresponded to the function that the participant intended to activate. If the video clip did not correspond, an error was made by the participant during the selection process.

Results: The questionnaires were analysed as in Evaluation 1 to produce SUS and NASA TLX results.

SUS: Analysis using the Adjective Rating Scale revealed that touch-based interaction achieved a score of 75.7 ('Good Usability'), whereas head-based achieved 36.7 ('Poor Usability'). This clearly highlighted that touch interaction was the most usable; with most participants finding interaction with the head challenging.

A second important result identified the safety of the emergency stop function with each interaction method. The results revealed a standard deviation of 4 seconds for the fingers, compared to 14 seconds for head tracking. The average stopping times were 4 seconds and 16 seconds respectively. The dramatically increased stop times for head tracking were observed to be the time taken to navigate to the Emergency Stop button using Switch Control, indicating that using the head is more unpredictable than fingers.

NASA TLX: The box plot comparisons in Figure 45 illustrate the differences in the workload experienced between touch and head-based interaction.

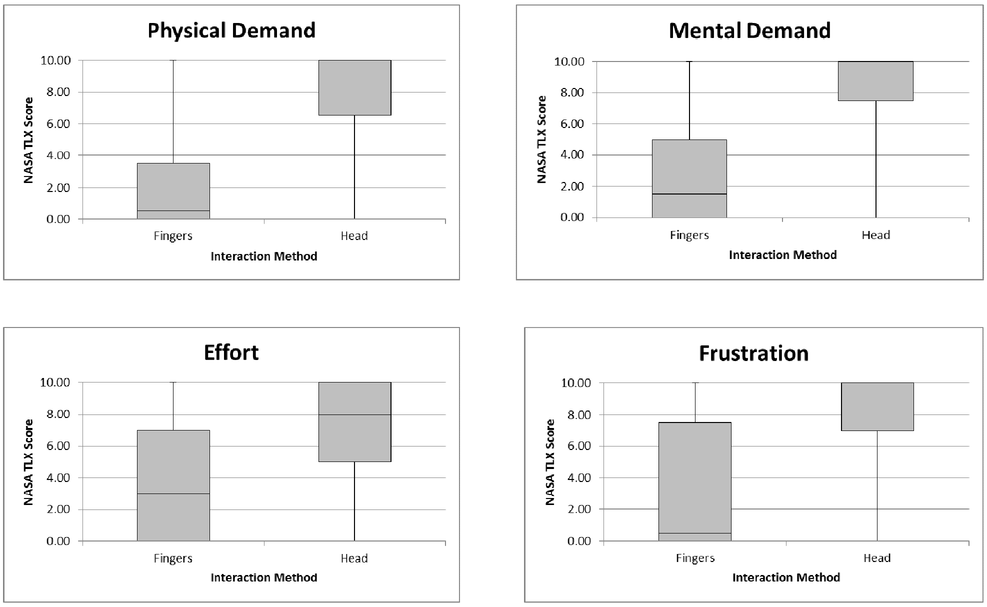

Figure 45: Box plot comparison of NASA TLX results in terms of Physical Demand, Mental Demand, Effort and Frustration

From the minimum, lower quartile, median, upper quartile and maximum values, it is evident that 'fingers' showed lower Mental and Temporal demands. As most participants found head-based interaction demanding, the medians for Physical Demand, Mental Demand and Frustration are equal to the maximum NASA TLX score of 10. Thus, proving that head interaction was more mentally and stressful to complete efficiently. A second important observation was the considerably higher Physical Demand for head interaction resulting in 65% of participants either not being able to sufficiently use Switch Control at all or finding it extremely challenging. The remaining 35% of participants experienced low workload levels when using the head due to having full range of neck movement. The limitations of head tracking are also reflected by the increased

Effort and Frustration levels compared to 'fingers'. Overall the box plots were fairly conclusive that in this particular instance, touch-based interaction was more effective than head interaction.

7.5 Evaluation 3 (Touch and Smartglass-based Interactions)

The third evaluation compared touch-based and smartglass interaction mediums to ascertain whether smartglasses could potentially be useful for people with reduced physical ability. The evaluation was conducted using the Recon Jet smartglass (described in section 2.8.6) with participants at the 2016 Mobility Roadshow. The simulation of SmartATRS that was used for Evaluation 2 was applied to this evaluation to eliminate the use of a vehicle and the ATRS components. There are no statistical results available due to the poor usability of the Recon Jet, it was decided not to conduct a controlled usability evaluation.

Participants: Visitors at the Mobility Roadshow were provided with an opportunity to test the Recon Jet. Out of approximately 10,000 visitors who attended the event, 36 chose to participate in the evaluation. The participants were a mixture of ages, had a mean age of 50 with varying physical conditions (including Cerebral Palsy, Spina Bifida, Arthritis and Polio) and either had manual wheelchairs, powerchairs or did not require assistance. The sample was representative to evaluate the Recon Jet to ascertain whether the technology would be a suitable interaction method.

Procedure: The planned procedure was to replicate the methods used in the Evaluations 1 and 2, i.e. NASA TLX and SUS questionnaires. However, it was discovered in Feasibility Trial 5 that the small buttons and display size of the Recon Jet was challenging even for people who did not have reduced physical ability. Therefore, it was decided that there was no purpose for an evaluation to be conducted at the Mobility Roadshow, as the participants' time was limited and the emphasis of attending the roadshow was to validate the framework.

The Recon Jet was to be connected to the SmartATRS network so that the user interface could be displayed whilst the SmartATRS simulation was open on a laptop to display the appropriate video clip of the function that was to be selected. Participants were asked to try on the smartglasses and see whether they could read the display. If the display was readable, the participants were to be instructed on the operation of the touchpad and buttons. Once a function was selected, the participants would observe the video displayed on the laptop.

Results: A majority of the participants required assistance to try on the smartglasses, as they did not possess the required dexterity. Due to the small text on the user interface (caused by the reduced display size), all participants were not able to read the button names and therefore, could not proceed to conduct the evaluation hence there was no need to complete the questionnaire. The participants also commented that the buttons used for selection were too small and not suitable for people with reduced finger dexterity.

This evaluation contributed to a framework by ascertained that smartglasses would not be suitable to include as an assistive technology due to the usability limitations identified. Evaluation 3 completed the controlled usability evaluations performed during the research.

7.6 Summary

Three controlled usability evaluations were performed to investigate the usability of keyfobs, touch, joystick and head-based interactions and smartglasses. An HTA was conducted to derive the SmartATRS tasks to be performed during the evaluations. Evaluation 1 was conducted the ATRS components installed in the author's vehicle and was performed in the outdoor environment. The results highlighted that touch-based was the most usable due to being familiar with the user group. Joystick was the second most challenging due to a steep learning curve created by the coordination required and keyfobs were most physically and mentally demanding due to small buttons with no user feedback. The results from Evaluation 2 also demonstrated that touch-based interaction was the most usable when compared to head interaction provided by iOS Switch Control. Typically, Switch Control was challenging due to the timing required for selection and the necessity to have a full 80˚ neck ROM. However, it was found that some participants could operate Switch Control who were not able to interact using touch. The final evaluation into smartglasses was not conducted as a full controlled usability evaluation due to poor usability identified prior to utilisation by people with reduced physical ability. In the evaluation participants tried on a Recon Jet and identified limitations to the usability due to a small screen size and selection buttons. Based on the findings of the evaluations, touch-based was revealed to be generally the most usable however, some participants preferred alternative forms of interaction due to their ROM and abilities. The knowledge obtained from the findings and results of the requirements elicitation phase, technology feasibility trials and controlled usability evaluations contributed to the development of the initial version of a framework that is described in Chapter 8.

Chapter 8 Research Results (iv) - SmartDisability Framework (Version 1)

8.1 Introduction

Based on the knowledge obtained from the requirements elicitation phase, technology feasibility trials and controlled usability evaluations, a framework was developed to recommend technology solutions. The recommendations were based on the ROM of the user, as this was seen as a key determinant for technology suitability based on the results of Evaluation 3. This chapter describes the initial conceptual model, the development of Version 1 of the framework (known as SmartDisability), validation results from semi-structured interviews and a focus group, and the suggested modifications.

8.2 Conceptual Model

The first phase of the development was to produce a conceptual model to identify the key elements of a framework, known as the 'SmartPowerchair Framework'. The name was established from the rationale that if technologies could be integrated into a powerchair, it would become 'smart' (as described in section 2.8.1)

The conceptual model shown in Figure 46 illustrates that the framework should consist of four pillars; User, Environment, Context and Technology, with each pillar being contributed to by a previous stage of the research. Descriptions of each pillar are provided as follows.

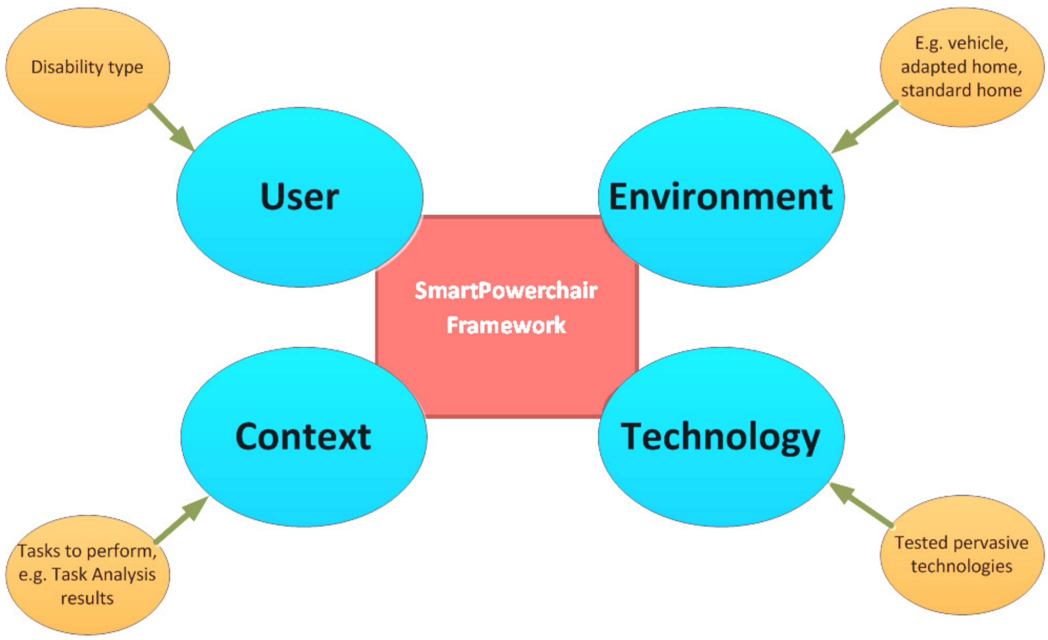

Figure 46: Conceptual model of SmartPowerchair Framework

User: The User pillar should consist of user categories derived by analysis of existing research into disability[6] types containing a new classification system based on a combination of the ICF and the Downton Scale to categorise potential users of the framework. The aim was to condense the diverse range of disabilities into a manageable number of categories, so that the common impairments could be determined which would then be used to ascertain the areas of the body that were affected by the disability. Technology recommendations could then be made depending on the areas where the user had greatest ability.

Environment: The requirements elicitation phase identified that people with disabilities encounter challenges in a variety of locations such as inside and outside of the home. Therefore, integrating technologies into the powerchair could assist in different environments and should be a consideration for the framework.

Technology: The results of feasibility trials and controlled usability evaluations should be the content of the Technology pillar, with only those that were deemed to be suitable for users with disabilities would be included (i.e. smartphone, tablet and smartglasses). Descriptions of the interaction methods for each technology (i.e. touch, joystick and head-based) should be documented based on the knowledge obtained from the evaluations. As the resulting SmartPowerchair was seen as a SoS (illustrated in Figure 46), the interoperability between other potentially integrated technologies should also be defined.

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[6] At the time of deriving the conceptual model, the negative connotation of the term 'disability' had not been highlighted, hence the use in the model and throughout the development of the initial version.

Context: The Context pillar should identify potential uses of the SmartPowerchair in terms of tasks that could be performed with the integrated technologies. As there were an extensive range of possible tasks that could be performed using the technologies, a HTA was conducted on the requirements elicitation results to identify the most challenging daily tasks for powerchair users, which was then used to map the technologies to tasks.

8.3 SmartDisability Development

The four pillars defined in the conceptual model were expanded to produce the initial six elements of Version 1 of the framework with the User pillar becoming the Disabilities, Range of Movements (ROM) and Movement Characteristics elements, the Technology pillar becoming the Interaction Mediums and Technologies elements and the Context pillar becoming the Tasks element. It was decided that the framework should be called 'SmartDisability' instead of SmartPowerchair as this was more appropriate to the aim of the framework which was to allow disability to become smart and potentially improve Quality of Life through independence. Also, the recommended technologies did not necessarily need to be integrated into a powerchair, as the technologies would be suitable for people with disability who do not require a wheelchair or powerchair. The SmartDisability Framework was developed as a spreadsheet with a separate worksheet for each element with images and references provided for information purposes. A revised conceptual model based on the internationally-recognised disability symbol illustrated the linear relationship between the elements, as shown in Figure 47.

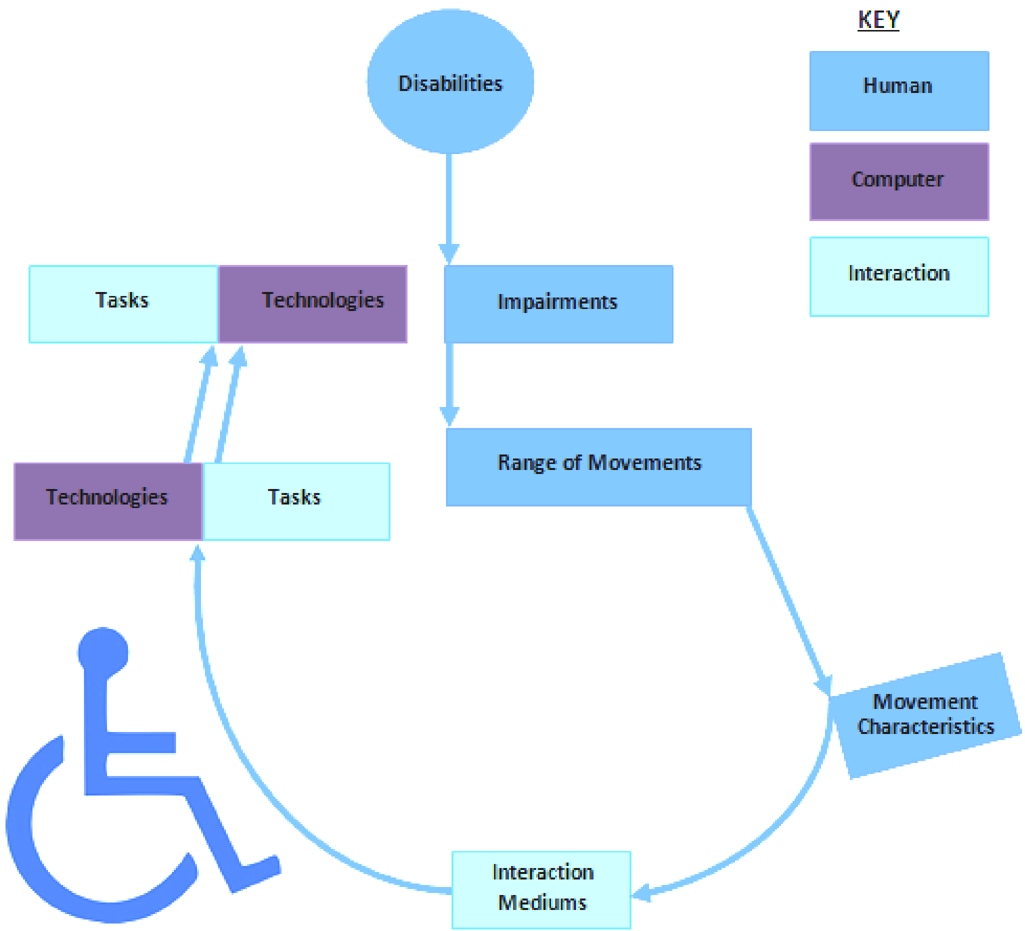


Figure 47: SmartDisability Framework conceptual model

The conceptual model identified that the elements were aligned to HCI in terms of Human (Disabilities, Impairments, ROM and Movement Characteristics), Computer (Technologies) and Interaction (Interaction Mediums) elements. Disabilities was input to the framework with the remaining elements being subsequently completed. The double arrow between Technologies and Tasks indicated that it was possible to move from Interaction Mediums to either Technologies or Tasks. Descriptions of each element are provided with extracts of the framework, full versions of the elements are found in Appendix K.

8.3.1 Disabilities

The Disabilities element identified the physical impairments associated with specific disability types such as an Acquired Brain Injury and Cerebral Palsy, to filter the range of disabilities into generic impairment types. The checkmarks inferred that the impairment is a contraindication of a disability and were colour-coded depending on the literature source, as shown in Figure 48.

Impairments	Acquired Brain Injury	Cerebral Palsy
Joints		
Limited neck movement	✓	✓
Limited shoulder movement	✓	✓
Limited elbow movement	✓	✓
Limited wrist movement	✓	✓
Limited finger dexterity	✓	✓
Limited ankle movement	✓	✓
Joint hypermobility		
Joint dislocation		
Scoliosis		✓
Muscles		
Contractures	✓	✓
Dyskenesia		✓
Atrophy		
Paraplegia	✓	✓
Quadraplegia / tetraplegia	✓	✓
Hemiparesis	✓	✓
Vision		
Visual	✓	✓
Cataracts		

Figure 48: An extract of the Disability element

Various sources were used to establish the relationships including the research performed by Andrews (2014) into ICF and the Downton Scale, and the disabilities of the participants in the controlled usability evaluations. The impairment types were categorised depending on the affected body parts; 'Joints', 'Muscles', 'Vision' and 'Sensory'. The inputs to the element was the disability type of the user, which was used to establish the affected areas of the body and became the inputs to the ROM element.

8.3.2 Range of Movements (ROM)

The aim of this element was to consider how impairment types identified in the Disabilities element restrict the ROM of an individual, therefore, categorising the impairments into associated ROM types, as shown in Figure 49.

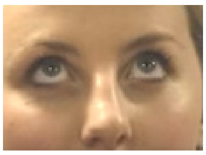
	Associated ROM		
Resulting Impairments	Neck	Shoulder	Elbow
Joints			
Limited neck movement	✓		
Limited shoulder movement		✓	
Limited elbow movement			✓
Limited wrist movement			
Limited finger dexterity			
Limited ankle movement			
Joint hypermobility		✓	✓
Joint dislocation	✓	✓	✓
Twisted spine	✓	✓	
Muscles			
Contractures	✓	✓	✓
Dyskenesia	✓	✓	✓
Atrophy	✓	✓	✓
Paraplegia			

Figure 49: An extract of ROM element

The list of resulting impairments was identical to those contained within the Disabilities element. Some of the defined relationships were obvious (e.g. limited neck movements is associated with neck ROM), however, others were formed as a result of analysing literature into specific disabilities (e.g. Atrophy, can affect the neck, shoulder and elbow). A blank cell indicated that the disability did not affect the particular ROM. The ROM element formed the inputs to ROM Characteristics, where depending on which type of ROM was affected by the individuals' impairment, the appropriate information could be obtained.

8.3.3 Movement Characteristics

The measurable features of each ROM type were identified in the Movement Characteristics element and included a number of characteristics that were used to determine how the ROM of the individual was affected by the impairments. The element contained Boolean statements to determine whether the user could perform each movement, as shown in Figure 50.



ROM Characteristic	Measurement Type		
	Max Degrees	Boolean	Max Percentage
Eye [2]			
Gaze up		Y/N	
Gaze down		Y/N	
Gaze left		Y/N	
Gaze right		Y/N	
Blinking		Y/N	
Mouth [4]			
Suck		Y/N	
Blow		Y/N	
Bite tongue		Y/N	
Move tongue left		Y/N	
Move tongue right		Y/N	
Smiling		Y/N	

Figure 50: An extract of the Movement Characteristics element

The movement characteristics defined the aspects that could be measured of each particular ROM that would either result in a Boolean value (i.e. the user can or cannot perform them movement), the maximum number of degrees the user can move (i.e. for neck movements) or the maximum percentage (i.e. visual acuity). The characteristics were categorised depending on the associated area of the body. The user would input their ROM into this element that would be used for the Interaction Mediums element to enable suitable mediums to be recommended.

8.3.4 Interaction Mediums

This element described the relationship between different interaction mediums and the required ROM for the interaction between a user and technology. The mediums contained within this element origination from the requirements elicitation surveys as technologies that were used by the participants. The element is shown in Figure 51.

Associated Characteristic	Interaction Mediums				
	Joystick [1]	Voice [6]	Head [3]	Eye [2]	Sip n Puff [4]
Eye					
Gaze up					
Gaze down					
Gaze left					
Gaze right					
Blinking					
Mouth					
Suck					
Blow					
Bite tongue					
Move tongue left					
Move tongue right					
Smiling					
Voice					
Speech intelligability					

Figure 51: An extract of the Interaction Mediums element

The cells of the element were highlighted where the interaction medium required a particular ROM characteristic. Example relationships included; an eye-based medium requires a user to gaze up, down, left, right or blink, an assistive technology device known as Sip 'n' Puff that requires a user to interact through sucking and blowing (Origin Instruments Corporation 2017) and gesture control that enables users to create gestures with their hands to interact with devices (Platz and Clothier 2015), but is only suitable for users who have full elbow, wrist and hand ROM. The outputs of the element was a list of interaction mediums that were suitable for the user and represented the inputs to the Technologies element with any mediums that required a ROM that the user did not possess, being omitted from the recommendation.

8.3.5 Technologies

The Technologies element (Figure 52) identified a range of specific technologies that could be operated through each interaction medium, such as smartphones, tablets and built-in eye tracking. It is recognised that there are other technologies available, which could be included in the element at a future time.

Interaction Mediums	Technology			
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]	Built-in Eye Tracking [4]
Joystick				
Voice				
Head				
Eye				
Sip n Puff				
Foot				
Chin				
Fingers				
Brain activity				

Figure 52: An extract of the Technologies element

Eye tracking could either be a built-in feature of a device (e.g. smartphone) or stand-alone, which specifically captures the eye movements of the user. Momentary switches enable the user to interact with devices by pressing buttons located in any position, e.g. the headrest or arm of a powerchair. A rear view camera would assist the user with manoeuvring from a live view on a smartphone or tablet attached to the powerchair (described in section 6.4. Most of the technologies had multiple methods of interaction, e.g. smartphones can be used by either fingers, joystick, head, eye, 'Sip n Puff' or voice, whereas built-in head tracking could only be used with the head. Evaluation 3 proved that iOS Switch Control was only suitable for users who possessed the necessary neck ROM.

The element provided technology recommendations that are suitable for the ROM of the users that were the inputs to the final Tasks element of the SmartDisability Framework.

8.3.6 Tasks

The purpose of the Tasks element (Figure 53) was to suggest daily tasks that could be performed with each of the technologies defined in the Technologies element. The tasks were derived from the requirements elicitation results as challenging tasks for people with disabilities to perform. Most of the technologies could support a variety of tasks whereas, some are specific e.g. a rear view camera can only assist with navigation.

Technology	Task		
	Navigating powerchair [1]	Operating vehicle adaptations [1]	Operating cooking equipment [1][2]
Smartphone			
Tablet			
Head Mounted Display			
Built-in Eye Tracker			
Stand-alone Eye Tracker			
Electroencephalogram			
Momentary Switches			
Rear View Camera			

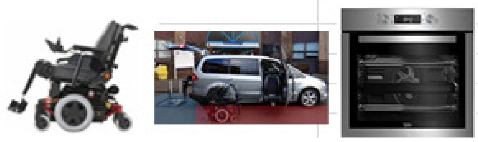


Figure 53: An extract of the Tasks element

The outputs of the element represented the conclusion of the framework with a list of recommended technologies and supported tasks that were suitable for the disability of the user.

The SmartDisability Framework therefore contained six elements that were created based on the four pillars defined in the conceptual model. In order to ascertain whether the framework would be suitable for the assistive technology domain prior to dissemination, it was necessary to conduct validations in two phases using semi-structured interviews and a focus group.

8.4 SmartDisability Validations

The validations for the SmartDisability Framework were conducted by interviewing people with disability at the 2016 Mobility Roadshow and establishing a focus group of domain experts from technology and healthcare backgrounds. The procedure and results from each validation phase are discussed.

8.4.1 Validation Phase 1 Procedure

The first phase of the validations was conducted at the 2016 Mobility Roadshow held at the Silverstone Circuit in Northamptonshire (Mobility Choice 2016), which was a UK consumer-based event for mobility products. A stand was set up in the Information Village of the roadshow containing screenshots of the SmartDisability Framework to attract the attention of the visitors. As an incentive for participation, visitors were provided with gift vouchers on completion of the validation. During the three day event, 35 participants with reduced physical ability validated the framework, as well as an employee from a manufacturer of environmental controls for homes. The manufacturer did not complete the framework as it was not relevant, however they provided feedback on the structure and content of SmartDisability. There were 19 male participants and 16 females, aged between 12 and 75 who had varying physical conditions. The most common conditions were cerebral palsy (7 participants) and rheumatoid arthritis (7 participants), with the remainder having conditions including, muscular dystrophy, paralysis and Post-Traumatic Stress Disorder. Table 18 provides an overview of the validation participants.

Table 18: SmartDisability validation Phase 1 participants

Pt No	Gender	Age	Conditions	Technology Awareness
1	F	42	Chronic fatigue/fibromyalgia	Internet
2	M	59	Cerebral Palsy	Remote Controlled TV and front door
3	M	67	Paralysis due to polio.	Wheelchair
4	M	74	Rheumatoid arthritis, stiff right leg	Scooter
5	M	67	Post-Traumatic Stress Disorder/cannot walk	Standard Scooter
6	M	66	Polio	Powerchair
7	M	62	Fredreich's Ataxia	None
8	F	67	Rheumatoid arthritis	Can-opener, adapted kitchen/bathroom, reclining bed, automated doors
9	M	74	Rheumatoid arthritis	Bath hoist
10	F	60	Rheumatoid arthritis, hemiparesis.	Automated tailgate, panoramic mirror in car, wheelchair lift
11	F	75	Tuberculosis in hip joints.	Walking frame, wheelchair, converted van.
12	F	65	Functional neuropathic spinal disease.	None
13	M	30	Right lower leg amputee.	Scooter
14	F	24	Fredreich's Ataxia	Eye Gaze
15	F	23	Scoliosis	Wheelchair, adapted kitchen
16	M	61	Spastic quadriplegia	Adapted car
17	F	70	Muscular Dystrophy	Adapted kitchen, powerchair, adapted car as a passenger, shower seat and bath lift.
19	F	34	Spina Bifida	Adapted car, joystick, powerchair,
20	M	57	Fibromyalgia	Laptop, smartphone
21	F	62	Rheumatoid arthritis, depression, diabetes, adhesive arachnoiditis	None
22	F	61	Amputated leg, diabetes, Rheumatoid arthritis	Eye Gaze
23	M	39	Cerebral Palsy	Communication device for speech
24	M	64	Back injuries, Rheumatoid arthritis	smartglasses, smartphone
25	M	19	Cerebral Palsy	Dictaphone, Read and Write
26	F	19	Cerebral Palsy	Adapted car, ClaroRead
27	M	64	Multiple Sclerosis	Adapted car

Pt No	Gender	Age	Conditions	Technology Awareness
28	M	38	Post-polio syndrome	Many technologies
29	F	73	Failed back surgery-nerve damage.	Scooter, powerchair
30	F	16	Cerebral Palsy	Powerchair
31	M	12	Cerebral Palsy	PC, laptop, tablet
32	F	29	Cerebral Palsy	Phone applications
33	M	42	Paraplegia	Smartphone, joystick, voice control
34	M	40	Spinal Injury	Powerchair
35	M	46	Muscular Dystrophy	Powerchair
36	F	52	Complex and regional pain syndrome	Hand controls.

The participants were provided with the documents in Appendix L. The validation took a maximum of 20 minutes per participant and a spreadsheet was developed to record data obtained in the interviews, with a separate worksheet for each element of the framework. It was not necessary to complete the Disabilities element, as this was an information source describing the relationships between disabilities and potential impairments. Subject to participant consent, information was obtained regarding their contact details, gender, age, disability and their current awareness of technology (i.e. assistive technology that the participant uses in their daily life). The remainder of the validation was performed by capturing the participant's ROM in the elements described in section 8.3.

The Movement Characteristics element was used to capture the specific details of the participant's ROM, where questions were asked as to the types of movement that they were able to perform. The data collection spreadsheet was completed by using checkmarks under the relevant ROM that were affected.

This concluded the capture of the participants' disabilities and the remaining three elements were completed by utilising the knowledge contained within the framework, in terms of the mappings between ROM, interaction mediums, technologies and tasks. As the result of completing the validation, the participants were provided with a list of recommended technologies, interaction mediums and tasks that were deemed to be suitable for their disability. The participants were also provided with a questionnaire (shown in Appendix L) to obtain their feedback on the usefulness of the framework and any suggested modifications. The modifications are summarised in section 8.4.3.

Conducting semi-structured interviews at the Mobility Roadshow as part of validation Phase 1 was a valuable method of obtaining feedback on the framework from people with reduced physical ability and an assistive technology manufacturer.

8.4.2 Validation Phase 2 Procedure

Phase 2 of the validation comprised a two-hour focus group to validate the framework based on the domain experts' knowledge. The group was formed from invited academics and postgraduate students in the computing and healthcare domains at a University, and used elaborated scenarios derived by analysing the disabilities and impairments of the participants that performed the validation at the roadshow.

The activity began with an introduction to the SmartDisability Framework that introduced the conceptual model and the purposes of the elements, as some of the experts had not encountered SmartDisability prior to validation. The participants were familiarised with the elaborated scenarios defined in Appendix M. Each scenario comprised of a paragraph describing a fictional character in terms of their disability, technology awareness and

ROM. The character was given a name to allow easy identification in the validation, but this was not based on any of the participants' names at the roadshow to ensure they remained anonymous. An assumption was made on all scenarios that if there was no information regarding a specific movement, then it was not affected by their disability. Once the participants were introduced and familiarised with the framework, each element was validated in 15 minutes by using the elaborated scenarios. The focus group concluded with a 15-minute open discussion on the framework and the suggested modifications.

Prior to the validation, the author created interaction medium, technology and task recommendations for each of the scenarios based on the knowledge contained within the framework. The validation was performed as a group activity, whereby the participants evaluated each element individually using the scenarios. As in Phase 1, the Disabilities element was used for information purposes to ascertain whether the disabilities stated in the scenarios resulted in the impairments contained within the element. Using the information contained within the scenarios, the participants selected the necessary associated ROMs in the ROM element. The Movement Characteristics element was completed by using the additional information about the movements that the fictional characters could perform, e.g. Will cannot gaze left, right or blink. Based on the movement that the character could perform the Interaction Mediums element was utilised to produce suitable interaction mediums for the character. Using the mappings defined in the Technologies and Tasks elements, the appropriate technologies and tasks were also established.

Throughout the process, the participants were guided on how to use the framework to produce recommendations. The guidance was only required for a first elaborated scenario, as for the subsequent scenarios, the participants had learnt the structure of the framework and were able to produce recommendations without assistance. The recommendations created by the participants were compared with the ones produced by the author and were found to be identical, thus indicating the correct use of the framework by the participants.

This concluded the first two phases of the framework validation and the key findings are stated in the subsequent section.

8.4.3 Validation Phases 1 and 2 Results

The feedback from the participants of the semi-structured interviews and focus group were combined to produce a list of suggested modifications, as described below:

1. In total, 15 participants from both validation phases commented that the term ‘disability’ was deemed to have a negative connotation, which contradicted the aim of the framework to be positive about improving the Quality of Life for people with a reduced physical ability. The participants suggested ‘ability’ is more positive and would therefore, better suit the aim of the framework.
2. It was identified that there was negative terminology used within the framework, e.g. the term ‘impairment’ and identifying the movements that are not possible for the user to perform in the ROM element. The participants highlighted

the importance of positivity in terms of the users' abilities, as this avoids negative conceptualisation of physical difference.

The participants commented that the ROM element was not required as the mappings were obvious and it was possible to proceed directly from Element 1 to Element 3 (which did occur in the validation to save time).

3. One participant at the Mobility Roadshow had Poliomyelitis, which was a condition that had not been considered in the Disabilities element.

4. Participant 1 (a Hospital Consultant) identified that the content of the Movement Characteristics element was not only associated with ROM, as it included visual acuity and speech. The name 'Abilities' was suggested to be more appropriate as this encompasses all measured aspects of the body. Some of the terminology used within this element should be simplified, as users without a medical background may not be able to understand their meanings, e.g. elbow flexion and extension.

5. Four participants in the focus group suggested that it was not possible to define the abilities of the users by binary division (i.e. can and cannot perform an action) and there should be a graded scale to allow users to assess their own abilities.

6. Participant 3 (a Software Engineer) In the Interaction Mediums element, a joystick should not be included as this is a technology. The interaction medium of 'Brain activity' should be renamed to 'Brain' to only indicate the part of the body that is involved in the interaction, thus aligning to the

other mediums contained within the element. Arm and tongue were suggested as additional forms of interaction.

7. Based on the above changes, the Technologies element should be updated accordingly. Participants suggested that the rear view camera should not be included as a separate technology, as it is an input device controlled from a smartphone or tablet. It was identified to be not necessary to include different types of eye and head tracking as separate technologies as it is irrelevant to state whether it is stand alone or built in. This only added to the complexity of the element.

8. Eleven participants from the Mobility Roadshow and the focus group were unsure of the purpose of the Tasks element that associated technologies with tasks. After clarification of the purpose, it was suggested that the element should map interaction mediums to tasks, but technologies should also be included. It was viewed that the 'Outdoor Activities' column of the element was ambiguous as there is a wide variety of tasks that could be performed outdoors.

9. Five participants in the focus group identified that the Boolean relationships shown by highlighted cells in the Interaction Mediums element to indicate that an interaction medium requires a specific ability is not representative of the real world. There are different ways in which users could interact with technology, e.g. using either the left or right hand.

10. Similar to Modification 9, these participants also commented that the Boolean mappings in the Technologies element to indicate whether a technology can be controlled through an interaction medium should be improved. This was due to

each interaction medium requiring a different level of effort to be exerted.

8.5 Conclusion

The framework originated from a conceptual model consisting of four pillars relating to the user, environment, context and technology aspects to be considered when producing technology recommendations. The pillars resulted in Version 1 of the framework being developed containing six elements that was named SmartDisability with the aim of allowing disability to become 'smart' through improved Quality of Life and independence. The conceptual model for SmartDisability was based on the disability symbol to illustrate the linear relationships between elements. The framework elements were developed as tables with the cells representing the mappings between the components including disabilities, impairments, ROM and technologies. SmartDisability was validated in two phases and involved the user community of people with reduced physical ability at the Mobility Roadshow and experts from the computing and healthcare domains. The validations identified nine modifications to the framework that would be implemented to develop Version 2 of the framework known as SmartAbility, described in Chapter 9.

Chapter 9 Research Results (v) - SmartAbility Framework (Versions 2 and 3)

9.1 Introduction

The suggested modifications resulting from the SmartDisability Framework validations were implemented to develop Version 2 of the framework, known as SmartAbility. This chapter describes the enhancements, the development of a structural model based on the Quality Function Deployment (QFD) tool to illustrate all mappings, the findings from a second set of validations conducted as semi-structured interviews with domain experts and description of the elements within the consolidated framework (Version 3).

9.2 Framework Modifications

The following modifications to the framework are numbered according to the validation suggestions described in section 8.4.3

1. The framework was renamed 'SmartAbility' to eliminate the use of the negative term of 'disability'. This suited the purpose of the framework that utilises the abilities of the users in order to recommend suitable interaction mediums and technologies. It was therefore, necessary to rename the Disabilities element to 'Physical Conditions', as this term would encompass all of the physical disabilities identified in the literature review.

2. All of the negative terminology was removed from the framework and consisted of modifying the contents of the Physical Conditions element by renaming 'Impairments' to 'Specific Conditions' and 'Limited Movements' to 'Partial Movements'. The ROM element was seen to be superfluous and removed, as it was possible to determine the Movement Characteristics from the Disabilities element. The removal of this element also eliminated the identification of the movements that a user is not able to perform.

3. Poliomyelitis was included in the Disabilities element associated with partial neck, shoulder, elbow, wrist, finger and ankle movements, contractures, atrophy, paraplegia, quadriplegia/tetraplegia and hemiparesis.

4. The Movement Characteristics element was renamed to 'Abilities' as this would encompass all characteristics. The names of the defined abilities were simplified to the synonym verbs: looking, blinking, seeing, sucking, blowing, biting, moving, smiling, speaking, lifting and bending. This reduced possible confusion, particularly with flexion and extension, which were renamed to 'moving'.

5. A traffic light grading scale was adopted due to the cultural significance of the three colours (Millar 2016) and introduced to the Abilities element to indicate the ease of action, with red implying impossible, amber being difficult and green indicating that the action was easy to perform. This scale enabled users to assess their own abilities to increase the suitability of the recommendations. The user would select a category that best describes their ease of action.

6. To address the comments from the validation, the joystick was removed from the Technologies element. The 'Brain activity' interaction medium was renamed to 'Brain' to align with other mediums that only describe the associated part of the body. Additional interaction mediums of arm and tongue were incorporated into the element, as these were feasible mediums that were not considered in the SmartDisability Framework.

7. To simplify the Technologies element, generic head and eye tracking were included instead of specifying whether it was stand-alone or built-in. The 'Momentary Switch' technology was simplified to 'Switch'.

8. Outdoor activities were removed from the Task element, as these tasks were considered outside the scope of the framework due to ambiguity and the large range of possible types. The Tasks element was subsequently restructured by applying Interaction Mediums as rows, Tasks as columns and Technologies being the cell contents. This therefore mapped all three aspects of the recommendations provided by the framework. The colour coded radio buttons adopted were:

- Smartphone
- Tablet
- Head Mounted Display
- Eye Tracker
- Head Tracker
- Electroencephalogram
- Switches

The radio buttons indicated which technology could be used via the interaction mediums to perform the tasks. A cell containing more than one symbol; indicated that a variety of technologies could be used to accomplish the task. A blank cell implied that there were currently no technologies that supported the specific tasks through the interaction mediums.

9. An alternative mapping method was developed for the Interaction Mediums element that was based on QFD, where symbols were used to indicate whether an ability was mandatory for an interaction medium or optional. The devised symbols were:

   ● Mandatory ability required

   ○ Optional ability required

   Mandatory ability implies that the user needs to possess the ability in order to successfully interact with the medium, whereas optional ability indicates that the user requires at least one of these abilities to operate the interaction medium. Orange was chosen as this colour had not been used in the other elements.

10. The mappings shown in the Technologies element were enhanced by applying QFD to devise four symbols to represent different types of ability in terms of agility, visual acuity and clarity. The rationale of the types was obtained

from the controlled usability evaluations, whereby a solid symbol represented high levels required and a white symbol indicated low levels, as shown below:

- ■ High agility
- □ Low agility
- ▲ High acuity
- △ Low acuity
- ◆ High clarity
- ◇ Low clarity

Agility indicates the motor skills required to successfully operate the technology and was identified as a significant factor from Evaluation 3, where participants were not able to operate the Recon Jet due to the exertion required on the buttons. Participants also acknowledged that acuity and speech clarity were significant factors in the operation of technologies. Acuity was considered to be important, as participants with reduced visual acuity were not able to read the small display of the Recon Jet, whilst speech clarity was commented on as the key determinant for the successful interaction with voice-activated technologies. The symbols were selected so that each type of ability was represented by a distinct shape with all using varying shades of blue, as they were associated with the same element.

Following the implementation of the modifications, the resulting framework elements and the overall structure are described in the subsequent section.

9.3 SmartAbility Development

Based on the implemented framework modifications described in section 9.2, a revised conceptual model (shown in Figure 54) was developed to illustrate the new structure of the framework. SmartAbility contained five elements: Physical Conditions (containing Specific Conditions), Abilities (measured by Ease of Action), Interaction Mediums and Technologies. The model retained the structure of the recognised disability symbol as well as the alignment to HCI by classifying the first four contents associated with the Human aspect, the fifth content associated with the Interaction aspect and the final element concerned with the Computer aspect. The readability was improved of the conceptual model was improved through the user of lighter background colours.

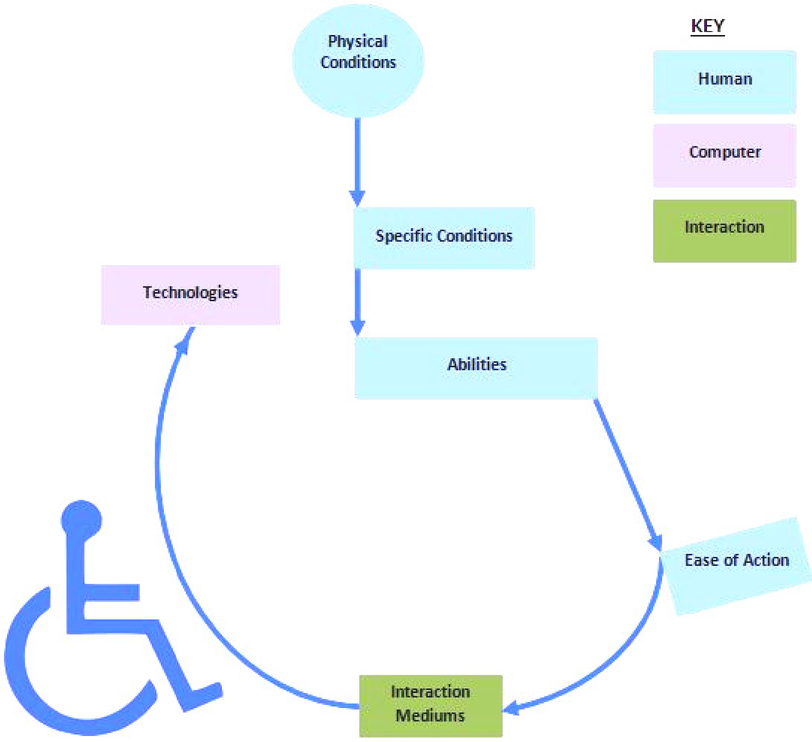


Figure 54: SmartAbility conceptual model

The framework continued to be a spreadsheet with a reduced number of work sheets due to SmartAbility now having five elements. To ensure that each element was unique, the mappings were illustrated by distinct identifiers including Likert scales, Boolean colour-coded radio buttons and checkmarks. As with SmartDisability, the elements contained appropriate images to describe the contents to users who may not be familiar with the technology. Descriptions of these elements along with extracts from the framework are provided and the full versions are provided in Appendix N.

9.3.1 Physical Conditions

The structure of the Physical Conditions element was not modified significantly from SmartDisability in that it filtered the range of physical conditions into generic categories, as can be seen in Figure 55.

	Physical Conditions	
Specific Conditions	Acquired Brain Injury	Brittle Bone Disease
Joints		
Partial neck movement	✓	✓
Partial shoulder movement	✓	✓
Partial elbow movement	✓	✓
Partial wrist movement	✓	✓
Partial finger dexterity	✓	✓
Partial ankle movement	✓	✓
Joint hypermobility		✓
Joint dislocation		✓
Scoliosis		
Muscles		
Contractures	✓	
Dyskenesia		
Atrophy		
Paraplegia	✓	
Quadraplegia / tetraplegia	✓	
Hemiparesis	✓	
Vision		
Visual	✓	
Cataracts		
Sensory		
Dizziness		
Speech		

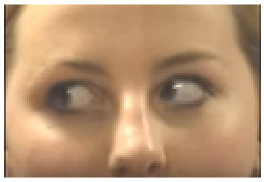
Figure 55: An extract of the Physical Conditions element

The terminology used and the name of the element were updated in accordance with Modification 1 and Limited Movements were renamed Partial Movements to satisfy Modification 2. The checkmarks inferred that the specific conditions were a contraindication of a physical condition and were colour-coded according to the literature source. The specific conditions were categorised depending on the affected body parts; e.g. 'Joints', 'Muscles', 'Vision' and 'Sensory'. The inputs to this element were the physical condition of the user, which produced a list of affected regions of the body, as inputs to the Abilities element.

9.3.2 Abilities

The element (illustrated in Figure 56) was renamed from Movement Characteristics to Abilities as suggested in Modification 3 with the aim of this element being to consider how the specific condition of the user affects their 'ease of action' in terms of 'Easy', 'Difficult' or 'Impossible'.

Abilities	Ease of Action		
	Easy	Difficult	Impossible
Eye [2]			
Looking upwards			
Looking downwards			
Looking left			
Looking right			
Blinking			
Seeing			
Mouth [4]			
Sucking			
Blowing			
Biting tongue			
Moving tongue left			
Moving tongue right			
Smiling			
...			


[2]

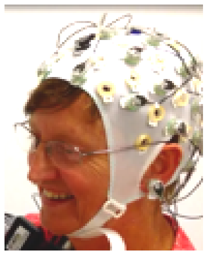


Figure 56: An extract of the Abilities element

Each of the abilities was renamed to simple verbs to represent the action concerned to assist users who did not have medical domain knowledge. As suggested in Modification 4, a traffic light style grading system was introduced to represent the three Ease of Action categories to create a simple choice for the user that avoids ambiguity. This enables users to select the category that best describes each of their abilities. The Abilities were classified under the categories of 'Head', 'Mouth', 'Voice', 'Neck', 'Shoulder', 'Elbow', 'Wrist', 'Hand' and 'Ankle' to represent the area of the body that was associated with the ability. The outputs of this element informed the Interaction Mediums element, where recommendations can be made depending on the users' abilities.

9.3.3 Interaction Mediums

To address Modification 8, the Boolean relationships in the Interaction Mediums used in the SmartDisability Framework were removed. This was replaced with a mapping method that utilised two symbols to represent Mandatory and Non-mandatory ability to differentiate whether there is a need to possess the ability, in order to interact with the medium. This mapping is shown in Figure 57.

Abilities	Arm [10]	Brain [8]	Chin [4]	Eye [2]
Eye [2]				
Looking upwards	○	●	○	●
Looking downwards	○	●	○	●
Looking left	○	●	○	●
Looking right	○	●	○	●
Blinking	○	●	○	●
Seeing	●	○	○	●

Ability:

●	Mandatory
○	Non-mandatory

Figure 57: An extract of the Interaction Mediums element

A filled orange circle indicated that the ability is mandatory, whereas a non-filled orange circle inferred non-mandatory ability. As can be seen in Figure 57, it is mandatory to be able to move the wrist in order to use arm-based interaction. For the non-mandatory abilities, the user must possess at least one of the abilities required for an interaction medium in order for it to be recommended, e.g. it is non-mandatory to see for brain interaction to be appropriate for the user. As a result of Modification 5, the joystick was removed as an interaction medium, 'Brain activity' was simplified to 'Brain' and the additional mediums suggested by the validation were incorporated into the element. The outputs of this element were the interaction mediums that were only deemed suitable for the user and formed the inputs to the Technologies element.

9.3.4 Technologies

Modification 9 was implemented by introducing the mappings to indicate levels of agility, visual acuity and clarity required to interact with technologies through specific interaction mediums (explained in section 9.2), as shown in Figure 58.

Interaction Mediums	Technologies		
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]
Arm	■	□	■
Brain			
Chin			
Eye	▲	▲	▲
Fingers	■	■	■
Foot			
Hand	■	□	■
Head			
Sip n Puff	■	■	
Tongue			
Voice	◆	◆	◆

Actions		
Using	■	High agility
	□	Low agility
Seeing	▲	High acuity
	△	Low acuity
Speaking	◆	High clarity
	◇	Low clarity

Figure 58: An extract of the Technologies element

The three types of ability were classified as 'Using', 'Seeing', and 'Speaking' actions to assist the user. Unique symbols and colours were adopted that were obviously different from those used in the other elements, with a solid symbol indicating high levels of ability required and an outlined symbol representing low levels. Modification 6 highlighted the need to simplify the head and eye tracking technologies to generic types and this was implementing by including 'Head Tracker' and 'Eye Tracker' as technologies. Figure 58 shows that a tablet requires lower levels of hand agility due to a larger screen size compared to a smartphone. The element also illustrates the different types of interaction mediums with technologies e.g. a smartphone could be operated with the arm, eye, fingers, hand, Sip 'n' Puff, and voice. This element provided recommendations of those technologies that were suitable for the abilities of the users and informed the final Tasks element of the SmartAbility Framework.

9.3.5 Tasks

The final element of the SmartAbility Framework was modified by removing the ‘Outdoor Activities’ task that was considered to be outside the scope as described in Modification 7. To enhance the mappings in the element, colour coded radio buttons were developed as described in section 9.2. The resulting element is illustrated in Figure 59.

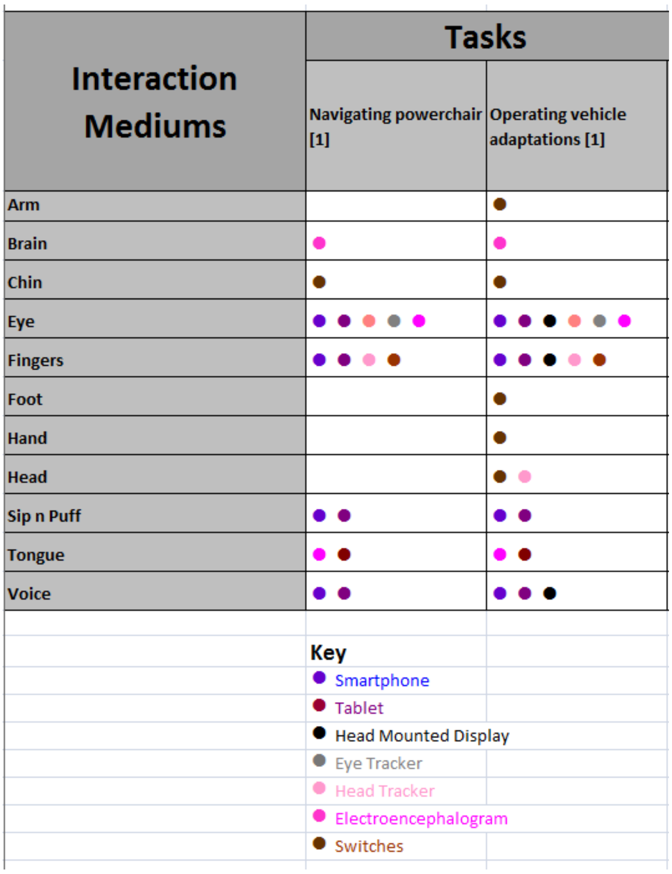


Figure 59: An extract of the Tasks element

The Tasks element therefore describes how tasks can be performed using given technologies via different interaction mediums. The colour coded radio buttons indicate the different types of technologies, hence multiple buttons can be include if several technologies support a task. If the cell is blank, then there are no technologies that have been tested in feasibility trials or controlled usability evaluations to support the specific tasks through the corresponding interaction medium. The outputs of this element are recommendations detailing the ways in which users can utilise suitable technologies to improve their Quality of Life. This element is the final aspect of the SmartAbility Framework and represents how the abilities of the user can be utilised. The relationships between the elements and their contents were defined in a structural model based on QFD, described in the next section.

9.3.6 SmartAbility Quality Function Deployment Model

The QFD tool was applied to provide a holistic view of the elements, mappings and the content of the SmartAbility Framework. The resulting tool adapts the original House of Quality (HoQ) matrix by utilising the symbols contained within the elements to illustrate the relationship. Due to the size of the HoQ, Figure 60 provides an overview of the entire HoQ, followed by enlarged versions of the four sections of the model shown in Figure 61–67, with the Abilities element being present in all sections.

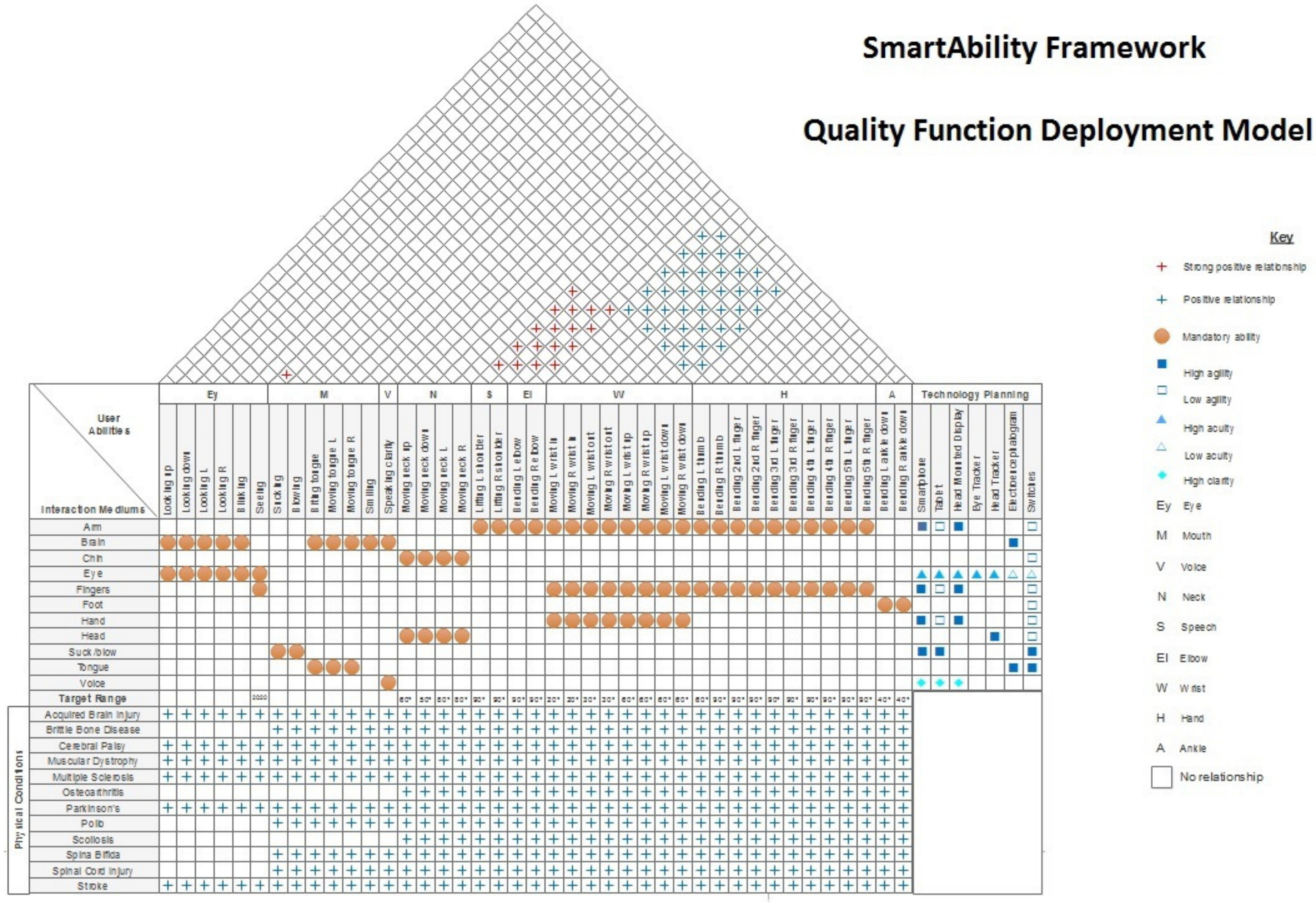


Figure 60: An overview of the SmartAbility House of Quality model

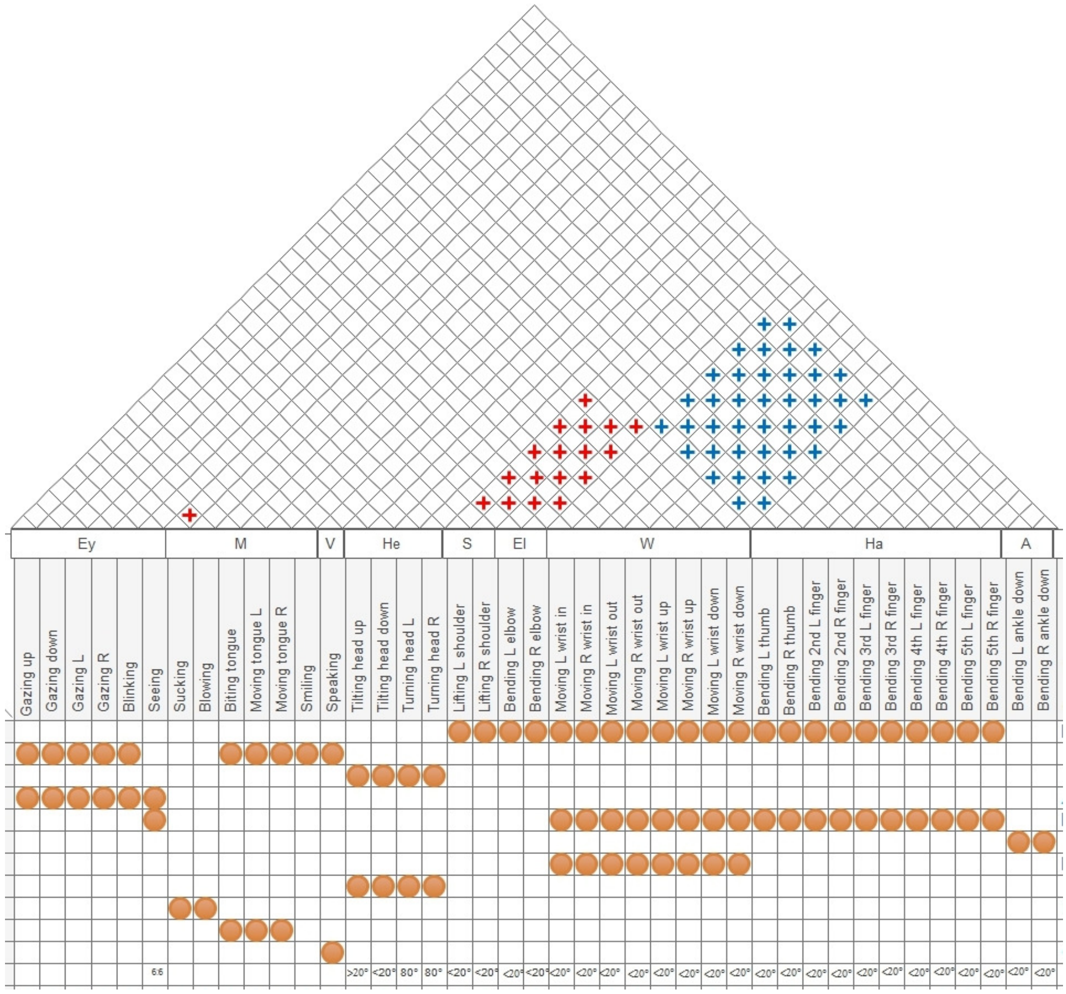


Figure 61: SmartAbility House of Quality model (Abilities and Ability Correlations)

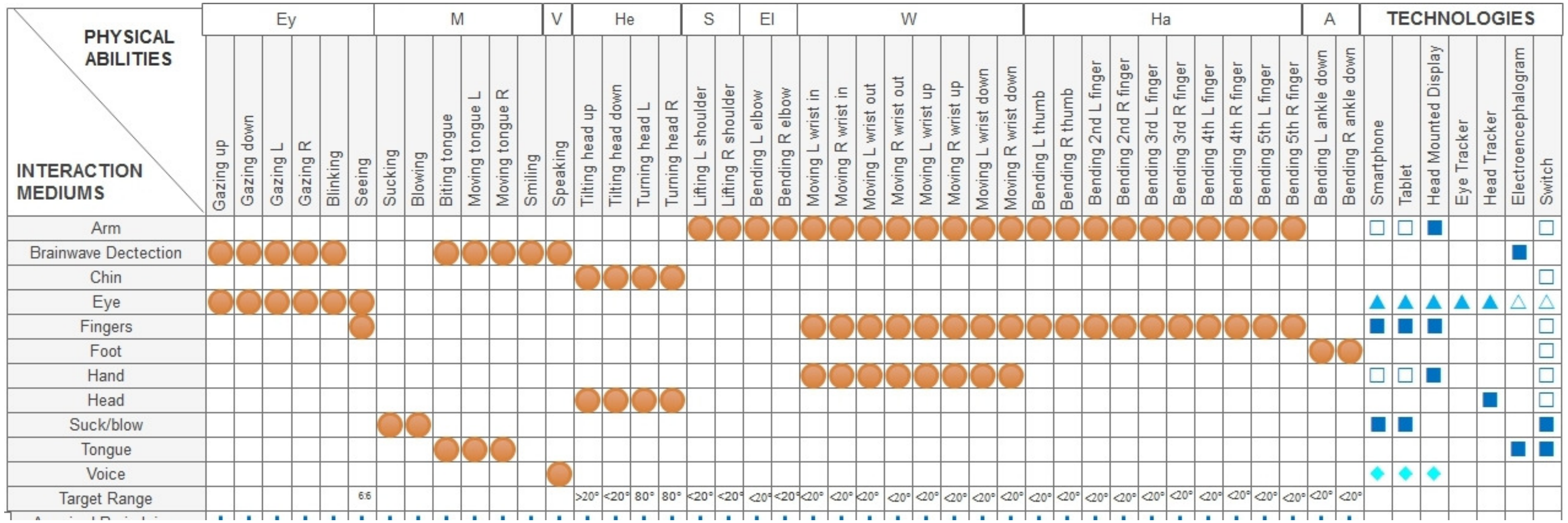


Figure 62: SmartAbility House of Quality model (Abilities, Interaction Mediums and Technologies)

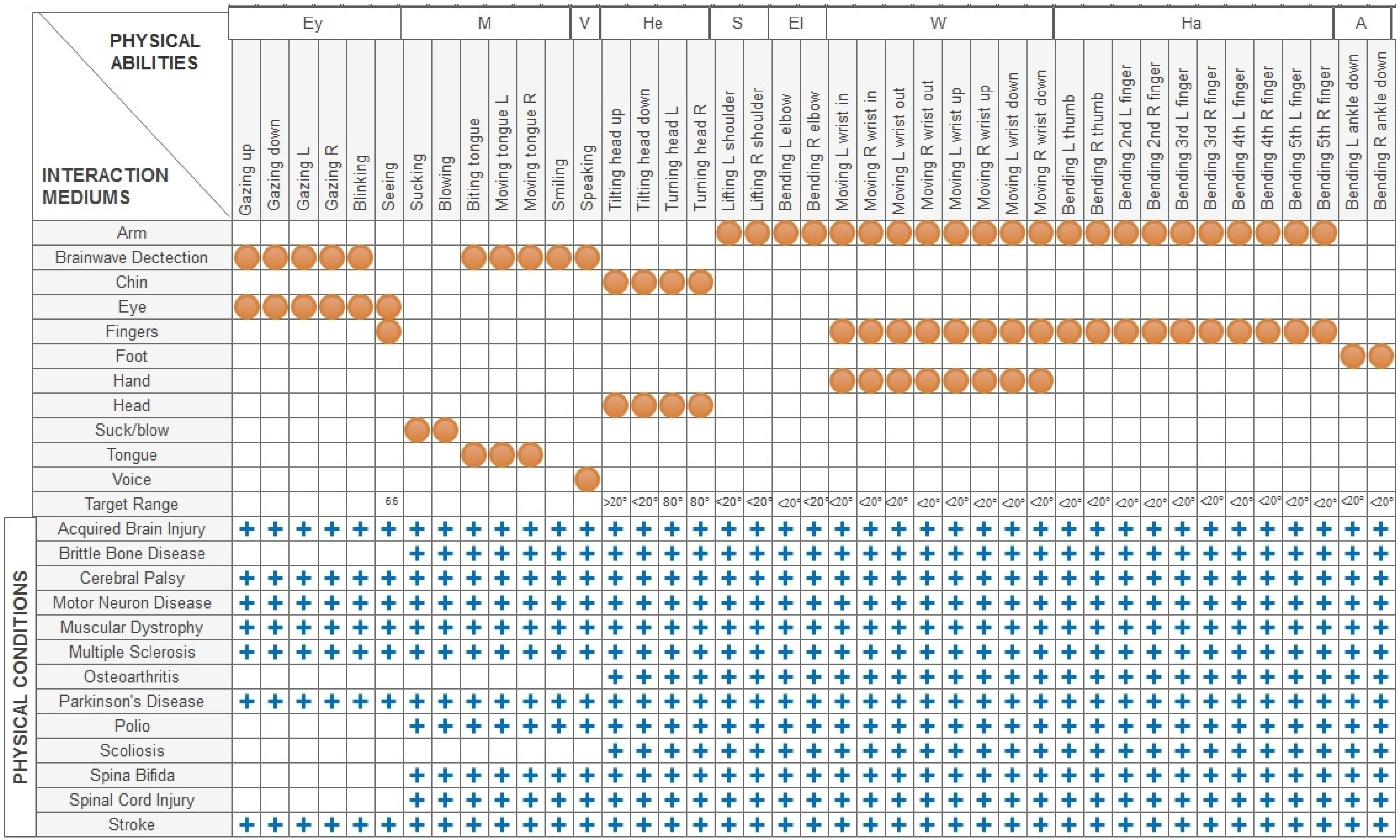


Figure 63: SmartAbility House of Quality model (Abilities and Physical Conditions)

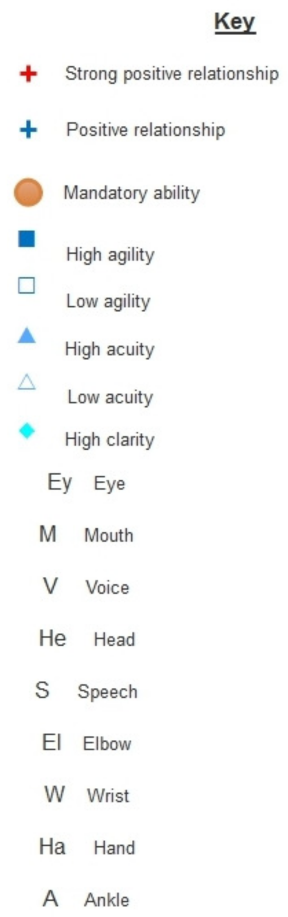


Figure 64: SmartAbility House of Quality model (Key)

The Customer Requirements of the HoQ represented the Interaction Mediums element of the framework where each medium was stated on a separate row. The Interaction Mediums correspond to a required Physical Ability that are stated instead of Technical Requirements in the HoQ. The mappings are illustrated by orange circles where a blank cell implies that the ability is not required for the Interaction Medium. The directions of the Abilities (i.e. left or right) have been abbreviated to 'L' and 'R' due to the space restrictions on the HoQ. The Abilities are categorised by the associated characteristics of: Eye (Ey), Mouth (M), Voice (V), Head (He), Shoulder (S), Elbow (El), Wrist (W), Hand (Ha) and Ankle (A). The target ranges for each ability were incorporated between the Interaction Mediums and Physical Conditions and contained the minimum measurements required to operate an Interaction Medium using an Ability. The Planning Matrix includes Technologies as these are viewed as solutions that could be implemented to improve Quality of Life. Each technology maps to an Interaction Medium that are illustrated using the symbols contained within the Technologies element. Instead of the Targets Matrix, the Physical Conditions that can reduce the abilities of users (identified in the literature review and from the participants of the controlled usability evaluations) are listed where a blue cross identifies that the ability may be reduced for a user with a particular condition. The purpose of this aspect of the HoQ is to illustrate the variety of conditions for which SmartAbility could be potentially useful. The final section of the HoQ is the Roof that describes the abilities that need to support each other when interacting with technology and are illustrated by red and blue crosses. This was determined by observations from the controlled usability evaluations but were validated with healthcare domain experts who had anatomical knowledge. The red crosses indicate that it is mandatory to possess both abilities in order for successful interaction, whereas blue crosses indicate that the user could possess either one of the abilities.

To compliment the HoQ, a Data Dictionary (Appendix O) was produced that included definitions of the used terminologies and symbols as well as the sources of the mappings established in the framework (i.e. literature or controlled usability evaluations). The purpose of the Data Dictionary was to increase the usability of the framework for users without medical or technical domain knowledge.

The HoQ, Data Dictionary and the individual elements of SmartAbility were subsequently validated in the second phase where technology and healthcare domain experts completed semi-structured interviews to elicit any further modifications that were required, as discussed in the following section.

9.4 SmartAbility Validation

After the modifications had been implemented in the SmartAbility framework, the third phase of the validation was conducted involving semi-structured interviews with domain experts from healthcare and computing.

9.4.1 Validation Phase 3 Procedure

The validation was conducted in the format of six semi-structured interviews using a questionnaire rather than a focus group as in

Phase 2. Interviews were used to obtain rich data from the participants, which suited the Interpretivism paradigm of the research. The feedback obtained from the participants could also be implemented in-between interviews to avoid identical comments being raised from the participants.

Each semi-structured interview had maximum duration of one hour, where a questionnaire (shown in Appendix P) first obtained background information on the participant including contact details, domain background and experience, before asking questions specific to each element and the HoQ. Some of the participants had performed Validation Phase 2 and were therefore, familiar with the framework. For those who did not have any previous knowledge, an introduction was provided using the conceptual model and explaining the contents and mappings within each element. The modifications made since the SmartDisability Framework were described and illustrated in the updated spreadsheet version. The HoQ was presented to participants and explained thoroughly, as QFD was an unfamiliar tool to those without computing domain knowledge. As in Validation Phase 1, the questionnaire concluded with Likert scales where a measure of the potential usefulness of the framework to healthcare and technology domains could be obtained. There was also the opportunity for the participants to express any other views regarding the framework.

9.4.2 Validation Phase 3 Results

The feedback obtained from the participants through the semi-structured interviews was collated into individual tables detailing their comments, the rationale and the action to be performed on the framework. These tables are provided in Appendix Q and include the general feedback obtained regarding SmartAbility. The key modifications for each element are stated below.

Physical Conditions

1. Should be grouped into two categories of acquired and congenital to be medically accurate. Following a further literature review, Acquired therefore, included Brain Injury, Motor Neuron Disease (included by Modification 4) Multiple Sclerosis, Muscular Dystrophy, Osteoarthritis, Parkinson's disease and Poliomyelitis, and Congenital included Brittle Bone Disease, Cerebral Palsy, Spina Bifida, Spinal Cord Injury and Stroke.

2. The terms 'Specific Conditions' was ambiguous and could be renamed 'Components of Disability' or 'Physical Limitations'. Both of these suggestions were considered to have negative connotations, so the term was renamed 'Associated Components', which had the same meaning and avoided negative terminology.

3. Spinal Cord Injury was classified as a congenital condition when medically it is an acquired condition. As the participant had medical domain knowledge, the condition was reclassified.

4. Motor Neuron Disease had not been considered in the element and it is a common condition where people benefit from technology. This condition was therefore, included as an acquired condition.

5. For Multiple Sclerosis, Parkinson's disease and Spinal Cord Injury, partial neck, shoulder, elbow, finger and ankle conditions had not been mapped. These conditions were also contraindications of Motor Neuron Disease (Modification 4) and needed to be included.

6. Brain Injury, Multiple Sclerosis, Parkinson's disease and Spinal Cord Injury can all result in speech impairment, which had not been mapped. These mappings were therefore included.

Abilities

7. The stated neck movements are actually head movements as it is not anatomically possible to move the neck without moving the head. These movements were therefore, reclassified as 'Head Movements'.

8. To improve the structure of the element, the abilities should be classified into generic categories, as a long list of abilities was considered to be difficult to read. Therefore, the categories of 'Head and Sense', 'Upper Limbs' and 'Lower Limbs' were introduced into the element.

9. The stated Target Ranges were generally too great to describe the ROM required for interactions with technology, as only subtle movements are required (i.e. 10˚ - 20˚ and not 90˚). Therefore, for all Target Ranges except Head Movements, '>20˚' were stated. As proven in the controlled usability evaluation, interaction with the head required an 80˚ ROM.

10. The definitions of the ‘Easy’, ‘Difficult’, ‘Impossible’, should be included in the Data Dictionary, as they are ambiguous without definition. These definitions were therefore included.

Interaction Mediums

11. Voice interaction does not necessarily require 100% speech clarity, as it could be possible to interact using by making a noise or a grunt sound. This ability was subsequently renamed ‘Speaking’ as a Boolean statement.

12. High Agility arm and hand-based interactions are not essential for a smartphone, as it is possible to operate the device with low agility. The mapping was amended to reflect this.

Technologies

13. The ‘Switch’ technology needed to be defined in the Data Dictionary as it was ambiguous.

14. The ‘Movement Agility’ characteristic was not applicable to all technologies, e.g. EEG. The term was renamed ‘Agility’, as this did not specifically refer to movement and it could be applied to all technologies.

Tasks

15. The element should be removed from the framework, as the participants agreed that it is sufficient to only recommend suitable Interaction Mediums and Technologies and not Tasks. There are an infinite number of possible tasks that can be performed with technology and therefore can be considered outside the scope of the framework.

Once all of the important modifications listed above were implemented, including any minor changes described in Appendix Q, the consolidated Version 3 of the framework was developed. These are described in the subsequent section.

9.5 Consolidated SmartAbility Framework (Version 3)

The modifications highlighted in section 9.4.2 were implemented on the SmartAbility Framework, resulting in Version 3 being developed. As the holistic structure of the framework had been modified since Version 2 due to the removal of the Tasks element, a revised conceptual model was developed shown in Figure 65.

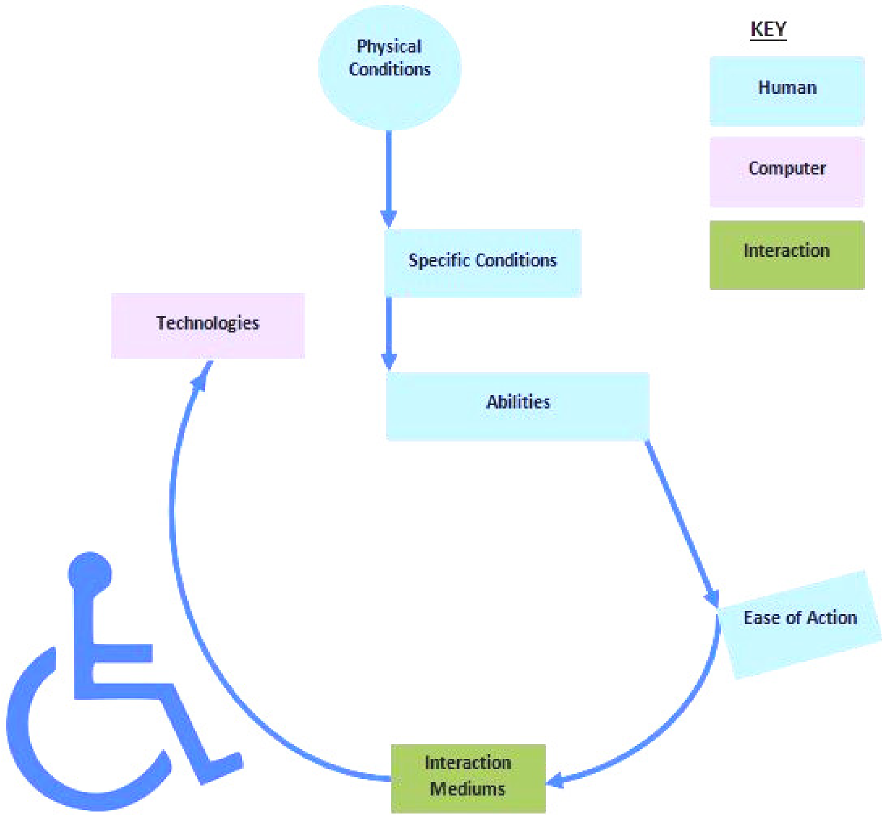


Figure 65: Consolidated SmartAbility Framework conceptual model

Extracts of the consolidated framework elements are provided in the subsequent sections, with full versions shown in Appendix R. To assist with understanding how the SmartAbility Framework would be utilised by users with reduced physical ability, the following user story (selected from the scenarios in Appendix M) will be applied to each of the elements in the subsequent subsections.

Becca is 33 years old and has functional neuropathic spinal disease. She has no technology awareness. She has limited Range of Movement of her neck, shoulder, wrist, fingers and ankle. Becca has a prosthetic right leg and her disability results in contractures, dizziness, vision and speech impairments. She has limited movement in her right shoulder, left wrist and left fingers.

9.5.1 Physical Conditions

The Physical Conditions were categorised into 'Acquired' or 'Congenital' and mapped to Associated Components that were considered to be contraindications of the conditions. These components remained grouped into 'Joints', 'Muscles', 'Vision' and 'Sensory' as in Version 1 and green check marks were included to infer the mappings that resulted from the validation. The element now includes Motor Neuron Disease as suggested. The consolidated element is shown in Figure 66.

	Physical Conditions (i)											
	Acquired								Congenital			
Associated Components	Brain Injury	Multiple Sclerosis	Motor Neuron Disease	Muscular Dystrophy	Osteo-arthritis	Parkinson's Disease	Polio-myelitis	Spinal Cord Injury	Brittle Bone Disease	Cerebral Palsy	Spina Bifida	Stroke
Joints												
Partial neck movement	✓ (blue)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (blue)		✓ (red)
Partial shoulder movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (red)	✓ (red)		✓ (red)
Partial elbow movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (red)	✓ (red)		✓ (red)
Partial wrist movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (red)		✓ (red)
Partial finger dexterity	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (blue)		✓ (red)
Partial ankle movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (red)		✓ (red)
Joint hypermobility									✓ (red)			
Joint dislocation									✓ (red)			
Scoliosis										✓ (blue)		
Muscles												
Contractures	✓ (red)	✓ (red)		✓ (red)			✓ (purple)			✓ (red)		✓ (red)
Dyskenesia		✓ (red)				✓ (red)				✓ (red)		
Atrophy		✓ (red)	✓ (green)	✓ (red)	✓ (red)		✓ (purple)	✓ (red)			✓ (red)	✓ (red)
Paraplegia	✓ (black)	✓ (red)		✓ (red)	✓ (red)		✓ (purple)	✓ (red)		✓ (blue)	✓ (red)	✓ (red)
Quadraplegia / tetraplegia	✓ (red)	✓ (red)					✓ (purple)	✓ (red)		✓ (red)		
Hemiparesis	✓ (black)						✓ (purple)			✓ (blue)		✓ (red)
Vision												
Visual	✓ (red)	✓ (red)								✓ (blue)		✓ (red)
Cataracts				✓ (red)								
Sensory												
Dizziness										✓ (blue)		
Speech	✓ (green)	✓ (green)	✓ (green)	✓ (red)		✓ (black)				✓ (blue)		

Figure 66: Consolidated Physical Conditions element

Applying this element to the user story, the associated components that characterise Becca are:

- "Partial neck movement"
- "Partial shoulder movement"
- "Partial finger dexterity"
- "Partial ankle movement"
- "Contractures"

- “Visual”
- “Dizziness”
- “Speech”

The outputs of this element are the abilities that could potentially be affected by the physical condition of the user. Further details of the abilities are elicited by the Abilities element.

9.5.2 Abilities

As shown by the extract in Figure 67, the Abilities were categorised into broad categories of ‘Head and Senses’ with sub categories of head, eye, mouth and voice, ‘Upper Limbs’ with sub categories of shoulder, elbow, wrist and hand and ‘Lower Limbs’ a sub category of ankle. The Target Ranges for all limb abilities were reduced to greater than 20˚, except the neck which requires 80˚ ROM. The ‘Head and Senses’ abilities were converted into Boolean parameters as the user either possesses the ability or it is impossible to perform. The ability names and images were renamed from Version 2, whereby simple synonym verbs were used to describe the ability illustrated with accompanying images.

Physical Abilities (vii)(x)	Target Ranges (iv)	Ease of Action		
		Easy	Difficult	Impossible
HEAD AND SENSES				
Head [3](ii)				
Tilting head upwards	>20°			
Tiliting head downwards	>20°			
Turning head left	80°			
Turning head right	80°			
Eye [2]				
Gazing upwards	Y/N			
Gazing downwards	Y/N			
Gazing left	Y/N			
Gazing right	Y/N			
Blinking	Y/N			
Seeing	6:6			
Mouth [4]				
Sucking	Y/N			
Blowing	Y/N			
Biting tongue between teeth	Y/N			
Moving tongue left	Y/N			
Moving tongue right	Y/N			
Smiling	Y/N			
Voice [1](v)				
Speaking	Y/N			
UPPER LIMBS				
Shoulder [3]				
Lifting left shoulder	>20°			
Lifting right shoulder	>20°			
Elbow [3]				
Bending left elbow	>20°			
Bending right elbow	>20°			

Figure 67: Consolidated Abilities element

Using the definition provided in the Data Dictionary, the user can select the 'Ease of Action' categories that best describe their abilities. Becca would select:

- "Tilting head upwards" = "Difficult"
- "Tilting head downwards" = "Difficult"
- "Turning head left" = "Difficult"
- "Turning head right" = "Difficult"
- "Gazing upwards" = "Easy"
- "Gazing downwards" = "Easy"
- "Gazing left" = "Easy"
- "Gazing right" = "Easy"
- "Blinking" = "Easy"

- “Seeing” = “Difficult”
- “Sucking” = “Difficult”
- “Blowing” = “Difficult”
- “Biting tongue between teeth” = “Easy”
- “Moving tongue left” = “Easy”
- “Moving tongue right” = “Easy”
- “Smiling” = “Easy”
- “Speaking” = “Difficult”
- “Lifting left shoulder” = “Difficult”
- “Lifting right shoulder” = “Difficult”
- “Bending left elbow” = “Easy”
- “Bending right elbow” = “Easy”

This forms the inputs to the Interaction Mediums element as abilities that are stated as ‘Easy’ or ‘Difficult’ would be suitable for interaction. Any ‘Impossible’ abilities would imply that the user is not able to interact using that particular aspect of the body.

9.5.3 Interaction Mediums

The mapping format was retained from Version 2, whereby a filled orange circle indicates Mandatory ability and a non-filled orange circle implies Non-mandatory ability. The only modification to the element was renaming the ‘Brain’ interaction medium to ‘Brain Wave Detection’, as it is the detection aspect that enables interaction and not the brain itself. An extract of the consolidated element is shown in Figure 68.

Ability:
● Mandatory
○ Non-mandatory

Physical Abilities	Interaction Mediums (ix)										
	Arm [10]	Brainwave Dectection [8]	Chin [4]	Eye [2]	Fingers [4]	Foot [4](viii)	Hand [1]	Head [3]	Sip n Puff [4]	Tongue [10]	Voice [6]
Head [3]											
Tilting head upwards	○	○	●	○	○	○	○	●	○	○	○
Tilting head downwards	○	○	●	○	○	○	○	●	○	○	○
Turning head left	○	○	●	○	○	○	○	●	○	○	○
Turning head right	○	○	●	○	○	○	○	●	○	○	○
Eye [2]											
Looking upwards	○	●	○	●	○	○	○	○	○	○	○
Looking downwards	○	●	○	●	○	○	○	○	○	○	○
Looking left	○	●	○	●	○	○	○	○	○	○	○
Looking right	○	●	○	●	○	○	○	○	○	○	○
Blinking	○	●	○	●	○	○	○	○	○	○	○
Seeing	●	○	○	●	●	○	●	●	●	○	○
Mouth [4]											
Sucking	○	○	○	○	○	○	○	○	●	○	○
Blowing	○	○	○	○	○	○	○	○	○	○	○
Biting tongue between teeth	○	●	○	○	○	○	○	○	○	●	○
Moving tongue left	○	●	○	○	○	○	○	○	○	●	○
Moving tongue right	○	●	○	○	○	○	○	○	○	●	○

Figure 68: Consolidated Interaction Mediums element

Based on the abilities that are 'Easy' or 'Difficult' for the user to perform, the suitable interaction mediums are recommended. The mediums that will be recommended for Becca are:

- "Brainwave detection"
- "Eye"
- "Tongue"

The recommended interaction mediums form the input to the final Technologies element.

9.5.4 Technologies

As with the Interaction Mediums element, the mapping format remained unchanged from Version 2. However, 'Movement Agility' was renamed to 'Agility'. As the 'Brain' interaction medium was renamed, this was reflected in the element. As suggested by the participants, the required arm and hand interaction required for the smartphone was reduced to low agility. Figure 69 shows the consolidated element.

Interaction Mediums	Technologies						
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]	Eye Tracker [4]	Head Tracker [6]	Electroencephalogram [9]	Switch [10]
Arm	□	□	■				□
Brain Wave Detection						■	
Chin							□
Eye	▲	▲	▲	▲	▲	▲	△
Fingers	■	■	■				□
Foot							□
Hand	□	□	■				□
Head					■		□
Sip n Puff	■	■					■
Tongue						■	■
Voice	◆	◆	◆				

Actions

Using	■	High agility
	□	Low agility
Seeing	▲	High acuity
	△	Low acuity
Speaking	◆	High clarity
	◇	Low clarity

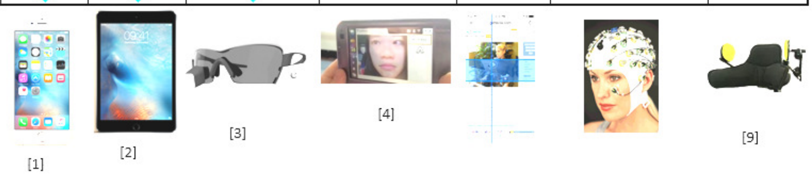


Figure 69: Consolidated Technologies element

Based on the recommended interaction mediums and the user's abilities, the suitable technologies are recommended with images being provided to inform the user. The recommended technologies based on Becca's abilities are:

- "Electroencephalogram" by "Brainwave Detection" and "Tongue"
- "Smartphone" by "Eye"
- "Tablet" by "Eye"
- "Head Mounted Display" by "Eye"
- "Eye Tracker" by "Eye"
- "Switch" by "Eye" and "Tongue"

This element represented the final aspect of the framework to be consolidated through validation using semi-structured interviews and focus groups involving people with reduced physical ability and domain experts from healthcare and computing. As this concludes the research results, a summary is provided to describe the key findings.

9.6 Research Results Summary

The requirements elicitation phase consisted of surveys and interviews provided to the user community of people with reduced physical ability. The phase highlighted the difficulties encountered in their daily lives and the technologies that could potentially improve their Quality of Life. Dynamic Controls provided the technology and framework requirements that needed to be met by the research based on their knowledge of the assistive technology domain.

Five feasibility trials of technologies were conducted using the SmartATRS case study, which informed the controlled usability evaluations and framework development. Trial 1 investigated EEG by using an actiCAP but as technology was considered to be challenging for people with reduced physical ability, it was not included as a controlled usability evaluation. Trial 2 established that TLD 1.0 was able to track facial features but because it relied on a MATLAB environment, which was not compatible with a smartphone. Trial 3 identified that TLD 2.0 was an improvement and provided increased performance, but due to limited programming knowledge, it was not possible to execute the algorithm on a smartphone. Trial 4 resulted in evaluating the two operating modes of iOS Switch Control and found that Point Mode was recommended for navigating the SmartATRS interface, as it required the minimal number of head movements. Trial 5 was performed with a Recon Jet smartglass, which was determined as being a feasible alternative interaction method, once the SmartATRS interface had been modified.

A greater understanding of the components and interactions in the concept demonstrator was obtained by implementing SoS using the models of Characterisation of SoS and the Two-dimensional SoS Model. The integration of a rear view camera to a powerchair demonstrated an example of SoS interoperability and the concept demonstrator was applied to the RASoS initiative to identify potential risks. The SoS analysis resulted in the formation of controlled usability evaluations to assess the suitability of multimodal interactions in the user community. Keyfobs, touch, joystick and head-based interaction methods and smartglasses were evaluated and it was highlighted that touch-based was predominantly most useful. Head-based interaction and smartglasses were suitable for specific users, with the suitability of all technologies being determined by the ROM of the user.

This finding contributed to the development of a framework to make technology recommendations for people, with reduced physical abilities. Originating from a conceptual model, Version 1 of the framework was developed, consisting of Disabilities, ROM, Movement Characteristics, Interaction Mediums, Technologies and Tasks. SmartDisability was validated through two phases involving the user community and domain experts to identify a number of improvements, including a change of name to SmartAbility. Version 2 of the framework was enhanced through mappings defined by symbols and colour codes and an optimal number of elements;

Physical Conditions, Abilities, Interaction Mediums, Technologies and Tasks. Along with an updated conceptual model, a holistic view of the framework was illustrated in the adaptation of the HoQ from the QFD approach. SmartAbility and the HoQ were subsequently revalidated through semi-structured interviews with further domain experts in order to produce a consolidated Version 3 with a number of enhancements, including the removal of the Tasks element. SmartAbility Framework Version 3 represents the key contribution and the application of the framework to a user story is illustrated. The entire research process is discussed in chapter 10.

Chapter 10 Discussion

10.1 Introduction

This chapter discusses the research; the key findings are described in terms of requirements analysis, technology feasibility trials, controlled usability evaluations and framework development.

10.2 Key Findings and Contributions

The research has contributed to a number of domains with key findings resulting from the research methods adopted. The results have been discussed in detail by the previous chapters and this section summarises the important aspects in accordance with the key, supplementary and potential future contributions to knowledge outlined in section 1.5.

10.2.1 Technology Recommendations (Key Contribution)

Based on the findings from requirements elicitation, feasibility trials and controlled usability evaluations, the initial version of the framework (known as SmartDisability) was developed. Placing users at the centre of designs was recommended by Norman (1988), which was the essence of the framework, as people with reduced physical ability were involved with the framework development process.

SmartDisability Development: The SmartDisability Framework presented the main aspects and relationships to be considered for producing technology recommendations determined by Disability Type and ROM, thereby satisfying Miles and Huberman's (1994) definition that a framework can be a visual presentation explaining the key concepts and the resulting relationships. It presented an enhancement over the existing ICF (WHO 2001a), which is the current international standard of classifying disability (Kostanjsek 2011). The framework applied principles from previous research performed by Andrews (2014) that mapped disabilities to the Downton Scale to categorise the resulting impairments into types such as motor control and senses. The knowledge obtained from Evaluation 2 involving iOS Switch Control ascertained that it was necessary to also consider ROM as a determinant for technology suitability where ROM can be defined as the movement around the axis of a joint (Kielhofner 2006). Specifically, only active ROM was considered by the framework, as this is concerned with movements that users could perform independently (Edugyan 2013) and included compensatory movements that users with reduced ROM could perform (Vasen et al. 1995) in order to successfully interact with technologies. The development of the SmartDisability Framework resulted in the creation of a conceptual model to illustrate the mappings between the elements. The model was based on the internationally-recognised disability symbol to highlight the applicability of the framework to the domain. Through the knowledge obtained from analysing the concept demonstrator as a SoS, it became evident that the framework could also be viewed as a SoS relying on the integration of a finite number of technologies (constituent systems) to achieve the higher goal of improving Quality of Life (Jamshidi 2009). As the framework SoS would evolve over time through the inclusion of new technology to enhance the capabilities, it adheres to the Open Systems approach (Azani 2009).

The key challenge of developing the SmartDisability Framework was to map all the relevant information from literature and previously described research findings into a conceptual model that presented clear information, thus adhering to the 'Comprehensible' Design for All criterions (EIDD 2009). The object was to convert the initial four pillars into six framework elements and their component parts. Consideration had to be given to the relationships between the elements through their commonalities i.e. impairments were associated with ROM. SmartDisability was published in the British HCI 2016 and SoSE 2016 conference papers, as well as in IEEE Transactions in Human Machine Systems.

SmartDisability Validations: The development process highlighted the requirement for a two-phase validation process to ensure the integrity and reliability (SWGFAST 2001) of a framework so that the recommendations produced would be suitable for the user community. The user community of people with reduced physical ability and manufacturers of assistive technologies was formed through the 2016 Mobility Roadshow, where feedback was obtained through completion of questionnaires. The integrity of the SmartDisability Framework was validated through a focus group of domain experts from computing and healthcare. This two-phased approach was a valuable method to obtain feedback from a variety of viewpoints and it became evident that the framework concept would be useful to all participants. The feedback obtained regarding the conceptual model was positive, although it was suggested that the readability could be improved. The overall lesson learnt from the validations was that participants enjoyed sharing their personal experiences and learning about new technology.

As a result of the questionnaires, a number of limitations of the SmartDisability Framework were revealed. One of the key criticisms that was shared amongst the participants was the use of the term ‘disability’ had negative connotations, along with some of the terminology such as ‘impairments’. This was an important aspect to consider, as the rationale of the framework was to be positive about the movements that users are able to perform. The domain exerts highlighted disabilities, interaction mediums and technologies that had not been considered in the framework and that the ROM element did not only concern ROM. The mappings within the element were found to be too simplistic due to being binary (yes/no) relationships that were not representative of the real world.

The validation process involving the user community was found to be challenging due to the limited time available to portray the framework rationale and structure in accordance with the ‘Perceptible Information’ Universal Design principle (Snider and Takeda 2008). To maximise the participants at the 2016 Mobility

Roadshow, monetary incentives were provided on completion of the questionnaires and flyers were distributed around the event to invite visitors to participate. A limitation that became apparent from the validations was that a paper-based method was adopted to record results, when it would have been more efficient to conduct this electronically. This would have eliminated the time required to retrospectively produce a results spreadsheet and the risks of inaccurate transcribing due to handwriting illegibility. The focus group was established with seven participants in accordance with the optimum focus group size as suggested by Bloor et al. (2000) to ensure that there was sufficient discussion, whilst being easy to manage. Intervals of 15 minutes were allocated to evaluate each element to maintain time management and ensure that the session was not longer than 2 hours in duration with equal opportunities for feedback from each participant (Guevara 2011).

SmartAbility Development: Through the validation of the SmartDisability Framework it became apparent that a second version needed to be developed to address the limitations. This version addressed all the feedback resulting in the SmartAbility Framework. The name 'SmartAbility' was more applicable to the framework rationale in terms of recommending technologies based on the abilities of the user. An updated conceptual model was produced with improved readability due to modifying the text and background colours. All negative terminology was removed from the framework, e.g. 'Impairments' was renamed 'Conditions' and the mappings within the elements were inverted so that they determined the actions that the user can perform rather than cannot perform, i.e. a 'can do' attitude, making the framework more 'Appealing' and socially acceptable. Therefore, satisfying this Design for All criterion (EIDD 2009). To align with the 'Simple and Intuitive Use' criterion, the number of elements was reduced to move the unnecessary ROM elements that did not provide additional value to the framework. The mappings were enhanced through deriving colour codes and symbols to represent the Ease of Action in a traffic light style, levels of abilities required for specific technologies and tasks that could be performed with technologies. A colour theme was developed in the framework to ensure that the symbols in each element were unique. Through the replacement of the original binary mappings, the framework accommodated the preferences and abilities of different users as stated in the 'Flexibility in Use' Universal Design principle (Snider and Takeda 2008). The experts provided additional conditions and abilities to be included in the Physical Conditions element based on their knowledge from the healthcare domain. However, it proved to be challenging to maintain a level of accuracy whilst avoiding medical terminology that may not be understood by users. This was achieved by utilising author judgement in terms of the language that communicated the required information efficiently (Snider and Takeda 2008). The healthcare domain experts also acknowledged that the Target Ranges for the abilities were generally too great, when only small movements can be used for interaction.

To compliment the SmartAbility Framework, a HoQ tool was developed to illustrate the mappings between the elements. The original HoQ for QFD formed the basis for the tool, where sections were substituted with the framework elements. Ensuring that the structure of the framework was accurately depicted by HoQ required careful consideration of the positions of each element and the symbols used to define the relationships. The numbers used in the QFD template were translated into the symbols from the framework, whilst the standard symbols were utilised to illustrate supporting abilities in the Roof section. The HoQ for SmartAbility aligns with the 'Perceptible Information' Universal Design principle (Snider and Takeda 2008) whereby the transparency of the framework structure is provided to users.

SmartAbility Validations: Based on the knowledge obtained from performing the first validation, it was considered necessary to conduct a validation of the SmartAbility Framework. To avoid peer influence, it was decided to conduct six individual semi-structured interviews with domain experts from healthcare and computing. To maximise the potential of the framework, modifications were made between interviews to avoid obtaining repetitive feedback. Semi-structured interviews were adopted so that key questions could be defined to maximise the time efficiency, whilst providing opportunity for the participants to elaborate and explore the various aspects of the framework (Britten 2006). Participants who had conducted the previous validation acknowledged that the framework had improved since the SmartDisability Framework. However, further enhancements were suggested. To improve the readability of the Physical Conditions element, it was suggested that conditions should be grouped into 'Acquired' and 'Congenital' to differentiate between those that occurred after birth and the conditions that existed from birth. This categorisation also increased the medical accuracy of the element and it was seen to not overcomplicate the structure. The healthcare experts expressed that all of the common conditions had been considered except Motor Neuron Disease, which was subsequently introduced into the element to comply with the 'Equitable Use' Universal Design principle (Snider and Takeda 2008). The term 'Specific Conditions', in this element was viewed to be ambiguous and a participant recommended that the term of 'Components of Disability' or 'Physical Limitations' should be adopted. However, both of these had negative connotations due to the words 'disability' and 'limitations' that had been removed from the framework during the development of SmartAbility. It was therefore decided to rename the section to 'Associated Components' that described the aspect of the element but remained positive. The remaining alterations suggested by the technology experts was that the accuracy of the mappings in the Interaction Mediums element needed to be improved, e.g. high agility is not necessarily required to operate a smartphone. Implementing the modifications ensured that the framework aligned to the 'Comprehensible' Design for All criteria (EIDD 2009), by providing clear information.

A participant commented that the framework did not consider combinations of movements or output devices. It was decided not to address the first comment due to there being numerous combinations of possible movements and this would significantly increase the complexity of the Abilities element and it was important to maintain the simplicity of the framework to align with Universal Design and Design for All. An assumption was therefore, added that only individual movements were to be considered by the framework. Similarly, output devices were assumed to be outside the scope of the framework as input devices are key to determining how users interact with technologies. Several of the participants highlighted that as there are an infinite number of tasks that can be performed with technology, it would be acceptable for the framework to finish with Technologies, thus removing the Tasks element. It was agreed that tasks should be considered outside the scope of the framework. Explaining the HoQ tool to participants who did not have technical domain knowledge proved to be challenging, as on initial inspection, the tool appeared complicated and difficult to comprehend. On explanation of the component parts, participants obtained understanding and the knowledge that the HoQ was useful to provide a holistic view of the framework. It became apparent that participants found comprehending the Roof challenging and required explanation of its purpose (i.e. Abilities that support each other). However, this section of the HoQ was retained as it contributed to knowledge obtained from the controlled usability evaluations as to which abilities were related.

The final validation phase highlighted that the framework had improved since the initial version but it would be necessary to develop Version 3 to satisfy the remaining comments. Version 3 represented the consolidated version of the framework as part of the third contribution to knowledge of the research. Establishment of the framework illustrated the importance to have an iterative development cycle (Spence and Bittner 2005) in order to produce a solution that was suitable for the intended user community and complied with the necessary Universal Design and Design for All principles and criteria.

The development of Versions 1 and 2 of the framework satisfied this contribution to knowledge to map interaction mediums and technologies to the physical abilities of the user. The findings from the SmartDisability and SmartAbility development and validations have been published at the British HCI 2016 and SoSE 2016 conferences as well as in the IEEE Transactions on Human Machine Systems. This is the key contributions to knowledge of the research and it is anticipated that the future framework dissemination will provide potential future impact contributions, as described in section 10.2.4.

10.2.2 Potential Assistive Technologies (Supplementary Contribution)

Feasibility Trials: Evaluating the five technologies of EEG (Brain Products 2017), TLD 1.0 (Kalal 2012) and 2.0 (TLD Vision s.r.o. 2017), iOS Switch Control (Apple Inc. 2016) and a smartglass (Recon Instruments 2017) determined whether these met the Williams-Zahir's (2015) definition of an assistive technology that enables independence for disabled and older people. The Design For All criteria of 'affordable' and 'appealing' were factors assessed during the trials and evaluations. The System Usability Scale (SUS) was applied to the evaluations to assess the Universal Design principles (Snider and Takeda 2008) of 'Flexibility in Use', 'Simple and Intuitive Use' and 'Perceptible Information', with NASA TLX being utilised to identify the 'Tolerance for Error' and ascertain whether the Physical Effort required for interaction was low. All of the controlled usability evaluations involved multimodal interactions as defined by Oviatt (2003), where two or more user input modes were combined to produce outputs. This included one of the natural interaction methods of touch as stated by Pfleging et al. (2012).

Feasibility Trial 1 highlighted that EEG technology is currently in its infancy due to the actiCAP being challenging to wear for users with reduced physical ability and having a 35-minute preparation time that was not practical and satisfy the principle of 'Simple and Intuitive Use' (Snider and Takeda 2008). The resulting brain activity from voice commands involving larger mouth movements were reliably detected indoors, but this finding could be different when used in an outdoor environment. The trial provided the direction of future research in that an alternative EEG technology could be evaluated with an ideal scenario being to integrate the technology into a standard garment such as a cap. A further challenge with this technology was the post-evaluation analysis of the EEG data, using the EEGLAB toolkit developed by Brain Products that operated in a MATLAB environment. Although the procedure for converting the brain signals to triggers for interaction was ascertained, implementation was not progressed due to the above identified limitations.

The second and third feasibility trials determined the capabilities of TLD algorithm for facial feature tracking with one key advantage over EEG being the non-obtrusive nature, as users were not required to wear any equipment fulfilling the 'Functional' Design for All principle (Snider and Takeda 2008). TLD 1.0 could accurately detect the nose however, when other features were tested (including the entire head), accuracy was reduced and there was a noticeable delay on resuming tracking after the feature re-entered the field of view. A major challenge of TLD 1.0 was the requirement of the technology to run in a MATLAB environment, which would not be feasible on a smartphone platform. The trial highlighted the potential of feature tracking through TLD and provided the basis to assess the second generation of algorithm. Feasibility Trial 3 demonstrated the improvements of TLD 2.0 compared to the first generation. It was established that although there was no noticeable difference in the tracking accuracy of the algorithm, the MATLAB environment was not required as TLD 2.0 executed as a C++ application in Windows. Despite the source code and documentation being provided, challenges were encountered during the customisation of the algorithm to suit a smartphone implementation. However, Trials 2 and 3 did establish that TLD had significant potential to provide non-obtrusive facial feature tracking in the future.

The feasibility of iOS Switch Control was assessed in Trial 4 with the technology having the advantage of being built into iOS, thereby requiring no additional cost and adhering to the 'Affordable' Universal Design principle (Snider and Takeda 2008). Through comparison of the two operation modes (Item and Point), it was discovered that both modes could be used to operate SmartATRS with varying levels of usability. By default, navigation using Item Mode involved numerous repetitive head movements that could result in increased physical strain to the user. To reduce the number of head movements, it was recommended that the Auto Scanning feature was enabled so that the technology scanned the interface automatically with head movements only required for selection. Switch Control was found to be most usable in Point Mode, as any position on the user interface could be selected in only two head movements. This represented a feasible form of navigation on a smartphone or tablet for users who did not have the dexterity to interact through touch or joystick based interactions. To enable SmartATRS to be controlled through Switch Control, an additional interface was developed with larger buttons that could be selected easily through Point Mode.

The Recon Jet was the subject of the final feasibility trial, as it was a non-immersive device that was capable of transmitting image data to the wearer whilst not affecting their view of the surroundings (Elder and Vakaloudis 2015). The device was compact and therefore, could be classed as a wearable technology as defined by Iqbal et al. (2016). Although more obtrusive than TLD and Switch Control, the smartglass had the benefit over EEG of resembling standard sunglasses, thereby adhering to the 'Appealing' Design for All principle (Snider and Takeda 2008). However, due to the initial purchase cost of the Recon Jet, it conflicted with the 'Affordable' principle. It was identified through the trial that the buttons on the device used for selection were small and difficult for the author who has finger dexterity. Implementation with SmartATRS had a similar challenge to iOS Switch Control, in that an additional interface needed to be developed. Besides reducing the size of buttons to suit the Recon Jet display, new JavaScript code was created that converted inputs from the selection buttons (identified as *KeyPress* events) to focus change events for the buttons. After this was achieved, SmartATRS could be controlled, albeit with a small user interface. The trial established that a smartglass was a potential alternative modality. The feasibility trials were essential to ascertain the types of technologies that had the potential to improve Quality of Life for people with reduced physical ability. It was necessary to subsequently controlled usability evaluations involving the user community to establish the technologies that would be suitable.

SoS Characterisation and Description: As the evaluations would consist of integrating existing systems into the SmartPowerchair concept demonstrator to create new functionality and capabilities (Sommerville 2014), a SoS perspective was adopted. The SmartPowerchair was considered as a Directed SoS created from the individual constituent systems including the standard components of ATRS (e.g. the platform lift and LIDAR unit) and the SmartATRS components (e.g. the relay board and smartphone). All of the constituent systems had the capability to operate independently, but only provided the functionality of the SoS when combined with the other constituent systems (SEBoK 2016a). The components were subordinate to the user interaction with the vehicle and were reliant on interoperability to provide the interaction between the powerchair and the vehicle. Analysis of the concept demonstrator using Characterisation of SoS (Henshaw et al. 2013) enabled the capabilities, purposes and functions of the individual systems to be defined and provided a detailed understanding of the systems. This analysis of the SoS increased the understanding of the operation of SmartATRS and thereby assisted the construction of the controlled usability evaluations. However, to further analyse the concept demonstrator, SoI (Kinder et al. 2012) was combined with Characterisation of SoS. SoI provided indications of the exploitation methods for the consolidated SmartAbility Framework. It emphasised the importance of an Utilisation/Support phase involving the user community to assess the suitability of the framework to the assistive technology and healthcare domains. The concept demonstrator provided an example of interoperability of SoS, whereby an 'off-the-shelf' rear view camera (Rear View Safety Inc. 2017) was integrated into a standard powerchair to assist with manoeuvring; a common challenge for powerchair users identified in the requirements elicitation phase. The live stream from the camera can be transmitted over Wi-Fi and displayed on a smartphone or tablet mounted to the powerchair via the freely-available GoVue application. The proximity indicators provided by GoVue appeared effective for judging distances, i.e. the width of doorways. The integrated camera generated significant interest from powerchair users at the 2016 Mobility Roadshow who were previously unaware that such a solution existed.

As the concept demonstrator was seen as a Directed SoS, it was necessary to consider SoS architectures. Generally, the design process of a SoS is challenging compared with traditional system design (Keating and Katina 2011), as the individual architectures of the constituent systems have to be considered, which can lead to differing or incompatible assumptions being made by the developers of the constituent systems (Sommerville 2014). Combining the constituent systems causes risks such as unintended resultant behaviour that does not occur when the systems are individual. The identification of risks in SoS was viewed as an important consideration that was not provided by the SmartAbility Framework. As a result, the concept demonstrator was applied to an initiative that focused on developing a risk analysis framework (RASoS). The initial version of the framework developed as part of a student project was based on the existing guidelines developed by NIST for mitigating risk in IT systems and identified the three key elements of risk being HSI, Interoperability Analysis and Emergent Behaviour. HSI concerns the identification of human involvement in the SoS through analysis of their relationships with the system by completion of an analysis form to ascertain the roles and responsibilities. Interoperability Analysis is a qualitative assessment into the types of risks that can adversely impact on interoperability and should be taken into consideration. The Emergent Behaviour aspect in the final stage of the risk analysis considers how potential risk can impact the users, systems and therefore, the utilisation SoS and the framework enables risk to be prioritised in terms of Low, Medium and High severity and for control measures to be stated. It is important to note that RASoS has not been validated through domain experts or applied to any other case studies other than the SmartPowerchair and therefore, does not form a key contribution of the research.

Controlled Usability Evaluations: Based on the knowledge obtained through the feasibility trials and SoS analysis, three evaluations were conducted comparing keyfob, joystick, touch and head-based interaction and a smartglass. To ensure equality during the evaluations, the technologies were individually customised to suit the user's ability where applicable, e.g. iOS Switch Control could be used with either a left or right head movement when the user's condition prevented the use of one particular direction.

The structure of Evaluation 1 was devised by creating the Hierarchical Task Analysis (HTA) that decomposed the overall tasks to arrive or depart in an ATRS-equipped vehicle into a series of subtasks. This provided a structured objective approach to understand the tasks that the users needed to perform (Hornsby 2010). Performing Evaluation 1 in an outdoor environment (as described in the risk assessment presented in Appendix I presented safety implications which were mitigated by providing detailed instructions based on the HTA. Comparing keyfobs, joystick and touch-based interaction with ATRS (Kliener 2008) and SmartATRS, Whittington et al. (2015a) highlight that touch-based was more predictable than the keyfobs, as all the participants managed to perform the Emergency Stop in less than 5 seconds, with an average of 2.2 seconds. By observation, it became apparent that the emergency stop using touch was generally easier and this was confirmed by a comment that "the Emergency Stop button is large and clear, particularly as it is red…. It was reassuring that the stop button would stop everything at once, which reduced worry and panic". It is important to note that as the participants did not have reduced finger dexterity; touch-based was considered easier than joystick. However, the author who has reduced finger dexterity preferred using joystick interaction because it is more accurate and quicker than touch-based. This was reiterated by a participant who remarked that using the joystick would be "physically the easiest to use for someone with reduced finger dexterity". However, participants commented that through repeated use they would become accustomed to operating the joystick, therefore, reducing effort and frustration. In terms of the keyfobs, some participants never managed to stop the lift as it was stowed before the emergency stop was performed. This would be unacceptable in an emergency situation, as it would potentially cause injury or damage. The cause of this time difference was summarised by one participant who commented, "I kept forgetting which buttons to press as there is no text on the fobs". The lack of text and the use of small, difficult to distinguish symbols is a major limitation of the keyfobs. Another important observation was that the temporal demand levels of the keyfobs were significantly increased compared with touch interaction. This difference showed the increased 'rushed' experience encountered when performing an emergency stop using the keyfobs. The results concluded that the keyfobs did not present 'Simple and Intuitive Use' and 'Low Physical Effort', which were apparent in SmartATRS (Snider and Takeda 2008).

At the time of completing the evaluation, it was challenging to find participants with reduced physical ability, as collaboration had not been established with Victoria Education Centre. It is recognised that this could have affected the results and a lesson learnt was that subsequent evaluations must involve the intended user community. Secondly, to eliminate safety risks from using a vehicle and ATRS components in an outdoor environment, a simulation of SmartATRS was developed and applied to Evaluations 2 and 3.

The second evaluation effectively demonstrated that in this particular instance, using fingers was less demanding than using the head due to Low Physical Effort required (Snider and Takeda 2008). However, a minority of participants were able to operate iOS Switch Control who were not able to interact with fingers. The importance of robust assistive technologies acknowledged by Metsis et al. (2008) that unusual situations must be supported by such technologies to cater for user errors, was reflected by the safety of the Emergency Stop task. The difference in physical demands for the two interaction methods was primarily the result of participants who did not possess the required coordination or neck ROM for iOS Switch Control to recognise the head movements. These findings led to the realisation that disability type is not the determinant as to whether a technology or interaction method would be suitable to a person with reduced physical ability.

The final evaluation promoted the awareness of a smartglass as a potential assistive technology instead of technology for sports and leisure. Due to the limitations discovered in the feasibility trial, it was decided not to perform a full controlled usability evaluation with SUS and NASA TLX questionnaires. Based on the participants at the 2016 Mobility Roadshow who evaluated the Recon Jet, it was determined that the technology required good visual acuity to view the user interface and dexterity to operate the small selection buttons on the device. This implied that the smartglass did not satisfy the 'Perceptible Information' Universal Design principle, as the required information was not communicated efficiently to the user regardless of their sensory ability (Snider and Takeda 2008). A challenge when performing the evaluation was to provide sufficient instructions for use, as it was not possible to view the display once a participant was wearing the technology. Knowledge was obtained that the Recon Jet had not been designed for people with reduced physical abilities although it attracted interest from able-bodied users including parents and carers.

The feasibility trials and controlled usability evaluations ascertained the technologies that had potential to improve Quality of Life for the user community, thereby informing the second contribution to knowledge of the research. These findings were published in the PECCS 2015 and SoSE 2015 conference papers, as well as in IEEE Transactions in Human Machine Systems. The SmartDisability Framework was subsequently developed to address the key contribution.

10.2.3 Technology Preferences (Supplementary Contribution)

The first phase of the research was to conduct requirements elicitation from the user community for people with reduced physical ability. Preece et al. (2015) suggest that these two methods are essential to achieve a human-centred design approach by involving the intended users early in the design process. By following the recommendations stated by Norman (2002), natural mappings between the intended tasks that were considered to be difficult and the suitable technologies were established through online surveys and semi-structured interviews, as techniques to increase the sample size as suggested by Marley (2016). It was necessary to offer the participants with a choice of formats to comply with the Equality Act 2010 regarding disability, to ensure that participants who were not able to input data into an online survey could equally contribute to the requirements. The semi-structured interviews were performed at the Victoria Education Centre using an identical question set to the online surveys and had the advantage of a captive audience compared with the low response from the surveys. The key findings provided a valuable insight into the challenges encountered by powerchair users in their daily lives, specifically:

- Dexterity and physical effort is required to open and close windows
- Narrow doors and obstacles present difficulties with navigating a powerchair
- Heavy external doors with locks (e.g. garage and front door) create barriers for powerchair users
- Heat generating appliances are potentially dangerous

These findings were identified through the elicitation of user requirements in chapter 4 and illustrated in the charts presented in section 4.3 informed the technologies to investigate in feasibility trials.

The comments from participants that “opening/closing windows will be impossible for me because they require manual dexterity that I don't have” and “opening/closing windows will be impossible for me because they require manual dexterity that I don't have”, highlighted the difficulties that they encountered with windows and doors. A participant stating that “the front door means I have to stand and pull the door towards me. The garage door is very heavy” revealed that coordination is required to open some doors. Appliances that generate heat were shown to be potentially dangerous based on a participant’s statement that “as I have no feelings from the chest down, I cannot sense heat so I have to be very careful when operating anything hot or even warm as I cannot feel it”. As well the challenges, participants also described technologies that currently assist them in their daily lives. Environmental controls, hand-activated doors and chin-operated joysticks were examples of technology currently installed in participants' homes. There was an interest expressed with smartphones operated by touch or head tracking, however eye or voice interaction was viewed to be less popular due to the participants having involuntary eye movements or speech conditions.

Establishing a user group for the requirements elicitation proved to be challenging due to the niche user group of people with reduced physical ability that use powerchairs and have sufficient cognitive ability to complete a survey. Despite 32 organisations being targeted with the online survey, the response rate was low. This could have been due to procrastination from the participants or that no immediate benefit was provided to the participants on survey completion.

Analysing the range of physical conditions of the user group, it appeared necessary to categorise the conditions to understand the individual needs. It was found that the conditions could be classified into the ICF domains of 'Structure of the nervous system', Structures involved in voice and speech' and 'Structures related to movement' (World Health Organisation 2001a) and the Downton Scale types of 'Motor Control' and 'Senses', as suggested by Andrews (2014). This enabled the participants to be grouped based on their abilities rather than disabilities.

Collaboration with a manufacturer of powerchair controllers was beneficial to elicit requirements in accordance with the Design For All principles (EIDD 2009) relating to safety and functionality and highlighted that technologies shall not be 'single solutions to fit multiple needs' (Requirement FR1). The customisation features of technologies were evident with iOS Switch Control where settings were adapted to improve the usability of the technology. The framework manufacturer requirement (FR2) identified the need to map the range of available of interaction mediums to the ability of the user, with only suitable technologies being recommended. Satisfying this requirement was dependent on the interoperability and the usability of the technologies.

Requirements elicitation represented the initial stage of the research (published in the Whittington et al. (2015b) conference paper) and satisfied the third contribution to knowledge and determined the direction of the subsequent technology feasibility trials and controlled usability evaluations.

10.2.4 Informing Domain Experts (Potential Future Impact Contribution)

The consolidated Version 3 of the framework will provide the means to inform domain experts of the applicability of SmartAbility in terms of potential interaction mediums and technologies that otherwise may not have been considered. Version 3 was a culmination of the research findings that were obtained through an interpretivism paradigm (Collis and Hussey 2014) where a variety of research strategies were adopted to obtain results. This included descriptive requirements, elicitation surveys and experimental case study adopted in the controlled usability evaluations. As discussed in section 10.2.1, the feedback obtained from the user community and domain experts during the framework validations were either addressed or considered to be outside the framework scope. The consolidated framework was enhanced through an optimum number of four elements, enhanced mappings through symbols and colour codes, incorporation of a variety of interaction mediums and technologies and reduced target ranges to recognise that only small movements are required for interaction. The exploitation of the SmartAbility Framework was mapped onto the Capability Maturity Model in which Paulk et al. (1993) define the types of organisations can develop software in terms of the levels of maturity. By considering the framework as software, SmartAbility was developed by a Level 1 organisation that did not have a prior reputation in the domain. In order to achieve successful exploitation, it will be necessary to approach Level 3 organisations that have well-defined, predictable processes for developing products (e.g. assistive technologies) or providing services (e.g. care) that ensure that all employees have sufficient knowledge of their domain.

The consolidated framework achieves the aim of the research by having the potential to improve multimodal interaction for people with reduced physical ability, as there is currently a void in the market for such a recommendation system. However, there are limitations with the consolidated version that require addressing including the areas considered as outside the scope, e.g. output devices and combinations of movements. These aspects could be introduced in the future through a fourth iteration of the framework. SmartAbility was developed in a spreadsheet format, which would not be suitable for direct exploitation to the domain. In order for the framework to be exploited and hence determine whether this contribution is satisfied, it will be necessary to develop a suitable platform to maximise exploitation potential.

10.2.5 Advising Framework Capability (Potential Future Impact Contribution)

Educating the public to understand the benefits that can be obtained is vital to conduct a Universal Design process where 'everyone is affected' and 'the design affects everyone' (Snider and Takeda 2008) and this principle was applied to the framework. This is achieved through the capability of recommending technologies that are suitable to user's ability.

It has been found that people with reduced physical ability are often unaware of the potential benefits that technology can provide to their lives. This was reflected in a user survey conducted by Ari and Inan (2010) that assessed how technology can offer equal opportunities to students in higher education. Their findings showed that Quality of Life was increased where students had access to a computer and the internet for communication. Quality of Life can be an indicator of the opportunities that are available to people from which choices and decisions can be made (Ontario Adult Autism 2016). Of the three forms of Quality of Life defined in section 1.2, 'Practical Becoming' will potentially be improved by the framework concerning the daily activities of the users. This is evident from the requirements elicitation phase where potential difficulties were discovered such as opening/closing doors and windows, which could be supported by technology e.g. appliances controlled from the smartphone (Panasonic UK & Ireland 2017).

In addition to people with reduced physical ability obtaining knowledge directly from the framework, healthcare professionals and assistive technology manufacturers could utilise the framework to obtain recommendations for their clients. The participants of the Validation Phase 3 highlighted potential uses of the framework, as described in Appendix R. The key comments were that rehabilitation medicine could benefit, where technology recommendations could be made to patients recovering from life changing traumatic events such as stokes and spinal injuries or temporary conditions resulting from accidents. The younger generation were also suggested as a beneficiary of the framework who could be supported in the education through assistive technologies. It was stated that allied health professionals such as General Practitioners, physio, occupational and speech therapists could utilise the framework to guide patients to new forms of technologies that they may not have considered. A participant mentioned that if the SmartAbility Framework was exploited as an internet-based application, it could potentially be useful to disabled living centres to assist and inform their clients. Manufacturers of assistive technologies could benefit from the framework through advertisements of their products. Routes to advising people with reduced physical ability about the capabilities of the framework could be achieved through promotion at exhibitions including the Mobility Roadshow, The OT Show for Occupational Therapists and the Naidex consumer show "dedicated to the care, rehabilitation, and lifestyle of people with a disability or impairment" (Prysm Ndex 2017).

In order for the framework to be exploited successfully, it would require periodic updating to ensure that it is aligned with the evolving field of technology. This would be achieved by the incorporation of additional interaction mediums and technologies that are mapped to the required user abilities. The user abilities could also be expanded if new methods of interaction using the body are discovered. The framework could also be enhanced by considering the mental abilities required to interact with technology. This would increase the potential user group to people with reduced mental ability as well as physical. In order to achieve this, research would need to be performed into methods of assessing the mental capacity of users. A second enhancement to the framework would be to investigate whether leisure activities for people with reduced physical ability could be recommended based on the actions that they can perform.

Through the knowledge obtained by conducting the research, it was realised that the final contribution had been met.

10.2.6 Adopting Positive Terminology (Potential Future Impact Contribution)

On commencing the research, the term 'disability' was adopted due to it being a recognised term (GOV.UK 2014). This was utilised through the initial requirements elicitation phase and subsequently for the name of the first version of the framework. When conducting Validation Phase 1 at the 2016 Mobility Roadshow, visitors commented that they viewed the term negatively and it should be modified. This was reiterated in the validation focus group and the framework was subsequently renamed as SmartAbility. Similarly, the negative terminology such as 'impairment' was removed to avoid negativity. From the author's personal viewpoint, 'disability' should not be used to characterise individuals, as the actions that users are able to perform should be promoted, hence the rationale of the framework.

By conducting a literature review, the terms of 'disability' and 'the disabled' are widely used in the community and are not considered negative. At the present time, it is important to be politically correct and this resulted in the abolishment of the term 'handicapped' (Rose 2004). The development of the framework should promote the phrase 'reduced physical ability' to describe physical abilities. This term was used as the research only considered physical conditions, but it could also be applied to mental conditions through the term 'reduced mental ability' or generically, 'reduced ability'. It will be challenging to obtain the recognition of this initiative but through the successful exploitation of the framework through an application, it is anticipated that this contribution will be achieved. The overall lesson learnt from the research that was reiterated by the visitors at the 2016 Mobility Roadshow and endorsed by the author is that it is important to focus on the positive and not on the negative.

This represents the final contribution of the research.

10.3 Summary

The first three contributions to knowledge were satisfied through the conduction of literature review, requirements elicitation, technology feasibility trials, controlled usability evaluations and framework development and the subsequent three will contribute to existing practices regarding assistive technologies and people with reduced physical ability. The first contribution ascertained the current challenges encountered in daily lives and the current interest in technology. This provided the basis for Contribution 2 where potential technologies were trialled for feasibility and evaluated with the user community. The obtained results were utilised to develop an initial conceptual model for a framework leading to the SmartDisability Framework as part of Contribution 3. This framework was validated through a two-phased approach of semi-structured interviews with the user community and a focus group. Based on their suggestions for improvement, Version 2 was produced and named 'SmartAbility'. A second iteration of the validation process was conducted using semi-structured interviews with domain experts who provided additional modifications that were implemented to develop a consolidated Version 3 of the SmartAbility Framework. The remaining contributions will be met through the successful exploitation of the framework to the assistive technology and healthcare domains through the development of a smartphone application. A significant contribution that has been achieved through performing the research is the realisation that the term 'reduced ability' can be promoted as an alternative to 'disability'. The final chapter summarise the realisation of the aim and objectives, critically evaluates the research and suggests future recommendations.

Chapter 11 Conclusions and Future Work

This chapter describes the extent to which the research aim and objectives have been realised. A critical evaluation along with recommendations for the assistive technology industry and suggestions for future research is also provided.

11.1 Aim and Objectives Realisation

The research led to in multiple outputs and contributions in a variety of domains. The key contribution to knowledge of the research was the development and subsequent validation of the SmartAbility Framework (hence Objective 4). However, this objective was achieved through obtaining the research results outlined in the previous chapters. Prior to the explanation of the realisation of the individual objectives, Table 19 provides a summary of the alignment of the research outputs to the aim, objectives, associated outputs and publications[7].

[7] Referenced in Appendix D.

Table 19: Summary of Research Outputs

Research Phases	Aim / Objectives	Outputs	Publications
State-of-the-art Review	1. To investigate the state-of-the-art focusing on reduced physical ability, HCI and SoS.	1. Existing classification frameworks for disability 2. Common acquired and congenital physical conditions 3. Equality legislations 4. Range of Movement as a determinant of ability 5. Applicable human-centred design principles 6. Applicable Design For All principles 7. Relevant SoS and SoI analysis techniques 8. Technologies to investigate through feasibility trials 9. Applicable industrial development models for framework exploitation.	PECCS 2015 EHF 2015 SoSE 2015 SoSE 2016 British HCI 2016 IEEE HMS 2016
User Requirements	2. To elicit user and stakeholder requirements for a concept demonstrator	10. Challenges for people with reduced physical ability 11. Potential technologies to improve Quality of Life	EHF 2015 SoSE 2015 IEEE HMS 2016

Research Phases	Aim / Objectives	Outputs	Publications
Manufacturer Requirements	2. To elicit user and manufacturer requirements for a concept demonstrator	12. Technology-related Volere requirements 13. Framework-related Volere requirements	N/A
Feasibility Trials	3. To conduct feasability trials and controlled usability evaluations of assistive technologies	14. iOS Switch Control feasible 15. Smartglass feasible 16. EEG not feasible 17. TLD 1.0 not feasible 18. TLD 2.0 not feasible	PECCS 2015 British HCI 2016 IEEE HMS 2016
System of Systems Characterisation	3. To conduct feasability trials and controlled usability evaluations of assistive technologies	19. Characterisation of SoS detailing SmartATRS components and interactions 20. Two-dimensional model describing framework exploitation 21. SoS interoperability demonstrated through an integrated rear view camera 22. Risk Assessment of SoS identifying risks to be considered	SoSE 2015 IEEE HMS 2016

Research Phases	Aim / Objectives	Outputs	Publications
Controlled Usability Evaluations	3. To conduct feasability trials and controlled usability evaluations of assistive technologies	23. Keyfobs least usable 24. Joystick interaction requires steep learning curve 25. Touch-based interaction most usable 26. SmartATRS simulation 27. Head-based interaction requires full 80˚ ROM 28. Smartglass interaction requires dexterity and good visual acuity	PECCS 2015 EHF 2015 SoSE 2015 IEEE HMS 2016
SmartDisability Development (Version 1)	4. To develop and validate a framework	29. Initial conceptual model consisting of four pillars 30. Revised conceptual model with seven defined elements	SoSE 2016 British HCI 2016
Framework Validations	4. To develop and validate a framework	31. Semi-structured interviews at Mobility Roadshow 32. Domain experts focus group 33. Suggested modifications	N/A

Research Phases	Aim / Objectives	Outputs	Publications
SmartAbility Development (Version 2)	4. To develop and validate a framework 5. To disseminate a framework and set of guidelines for the assistive technology domain	34. Implementing modifications 35. Change of name 36. Revised conceptual model with five optimum elements 37. Promote positive attitude 38. Enhanced mappings defined through symbols and colour codes 39. HoQ model defining element mappings 40. Data Dictionary defining mappings and key terminology 41. Validations through semi-structured interviews with domain experts 42. Suggested modifications	N/A
Consolidated SmartAbility Framework (Version 3)	Aim: To develop a framework to enhance multimodal interaction for people with reduced physical ability	43. Revised framework content 44. Updated HoQ 45. Updated Data Dictionary 46. Aim and Objectives realisation	PhD Thesis

The aim of the research has been achieved through satisfying the individual objectives. Due to being the key contribution to knowledge, the realisation of Objective 4 is described first. This is followed by the remaining objectives that achieved the supplementary contributions defined in section 1.5.

11.1.1 Objective 4: Framework Development and Validation

Objective 4 was realised by the iterative development of a framework, with each version being validated and enhanced by utilising the knowledge obtained from people with reduced physical abilities and domain experts from healthcare and computing.

The first version of the framework was named 'SmartDisability' and originated from a conceptual model consisting of the User, Environment, Context and Technology pillars, which subsequently evolved into the six elements of the framework. The Disabilities element was populated through the literature review of existing disability classification schemes and identified the physical impairments associated with disability types. As proven in Evaluation 2, ROM could be the determinant for technology suitability and hence, formed the basis of the second and third elements. The elements mapped the disabilities onto the parts of the body that could be adversely affected and defined the aspects that could be measured for each particular ROM. The fourth Interaction Mediums element mapped the ROM required in order to utilise different interaction mediums based on literature and the knowledge obtained from the controlled usability evaluations. The Technologies element identified the specific technologies that could be operated through each interaction medium and form the basis for the recommendations. The final Tasks element suggested daily tasks that could be performed with each technology. A conceptual model was derived that described the framework structure by replicating the internationally-recognised disability symbol.

The SmartDisability Framework was validated in a two-phased approach utilising people with reduced physical ability and manufactures of assistive technology at the 2016 Mobility Roadshow, as well as a focus group of domain experts from computing and healthcare. The validations identified a number of improvements to be made to the framework, most notably a change of name to avoid the negative connotation of the term 'disability' and the removal of all negative terminology, e.g. 'Impairments'. All of the modifications were addressed and Version 2 of the framework was developed, named 'SmartAbility'. The framework had an optimum number of five elements and the mappings in the Technologies and Tasks elements were illustrated through colour-coded symbols. Additional physical conditions were incorporated based on the participants and the knowledge from domain experts. To supplement the framework, a holistic view of the elements, mappings and content were illustrated in a House of Quality (HoQ) model adapted from the Quality Function Deployment (QFD) tool, with an accompanying data dictionary to explain the relationships.

The SmartAbility Framework, HoQ model and data dictionary were validated through the involvement of further domain experts from computing and healthcare via semi-structured interviews using questionnaires. Further modifications were suggested including additional physical conditions, abilities, interaction mediums and technologies to be considered, as well as the removal of the Tasks element. The participants acknowledged a significant improvement of the framework compared to SmartDisability.

By implementing modifications, a consolidated Version 3 of the SmartAbility Framework was developed to represent the main contribution to knowledge and that has been validated through the involvement of the intended user community and domain experts. The consolidated framework therefore realised the aim of the research.

The development of the SmartDisability and SmartAbility Frameworks have been the subject of publications at British HCI 2016, SoSE 2016 conferences and in the IEEE Transactions on Human Machine Systems journal.

11.1.2 Objective 1: State-of-the-art

This objective has been achieved by conducting a state-of-the-art literature review centred on physical ability, HCI and SoS principles and assistive technologies.

Classification frameworks were investigated in order to inform the Disabilities element of the SmartDisability Framework. It was identified that the current international standard for classification is the ICF (World Health Organization 2001a) that considers the health conditions and environmental factors that result in disability. Associated research conducted by Andrews (2014) was obtained that analysed the relationship between the ICF, Downton Scale and types of impairments. The aspects concerned with physical conditions formed the basis of the Disabilities element by mapping impairments to common types of disabilities also suggested by Andrews (2014).

Further information was obtained through a review of each condition and to reduce the range of disabilities, the conditions were classified into acquired or congenital depending on literary categories as to whether the conditions were caused at birth or at a later point in life, e.g. a traumatic event. To inform the development of the framework, it was necessary to consider the Equality Act 2010 to ensure that equal opportunities were provided to improve Quality of Life independent of the users' physical abilities. It was established by Evaluation 2 that Range of Movement (ROM) was a determinant for the users' abilities and hence a literature review was conducted into the different forms of ROM. It was determined that functional ROM was most relevant to the framework, as this concerned the minimal version required to perform daily living tasks comfortably and effectively (Vasen et al. 1995). Even though ROM could be accurately measured using a goniometer, this was not required for the framework as only a Boolean statement was required, i.e. the user can or cannot produce the movement.

The second domain to be investigated in the literature review was Human Computer Interaction (HCI), in particular Ergonomics of Human-system

Interaction, Universal Design and Design For All. Analysis of the ISO standard for Ergonomics of human-system interaction (ISO 9241-210:2010) identified the principles and criteria to meet in order to achieve a human-centred design process for the framework and the appropriate elicitation techniques including interviews and questionnaires. The recommendations stated by Norman (2002) for placing users at the centre of the design highlighted one that was particularly relevant to the development of the framework in that 'natural mappings between intentions and the required actions' should be followed. The Design For All criteria informed the assessment techniques of the technologies during the feasibility trials and controlled usability evaluations, in that the technologies could be safe, functional, comprehensible, affordable and appealing. These criteria could also be applied to the framework as the information provided to the users would need to be comprehensible. To support these criteria, the principles of Universal Design were reviewed and established other factors to measure during the trials and evaluations, such as 'Simple and Intuitive Use', 'Perceptible Information', 'Tolerance for Error' and 'Low Physical Effort' (Snider and Takeda 2008). To further inform the trials and evaluations, multimodal interaction was reviewed that highlighted the difference forms that users can interact with systems including speech, gestures, eye gaze and 3D sensors. The rationale behind the framework concerned multimodal interaction as it provided recommendations of different forms of interaction that were suitable to the users' abilities.

System of Systems (SoS) formed a section of the literature review as both the concept demonstrator (SmartATRS) and the framework itself can be considered as a SoS, established from the interaction between individual constituent systems. Techniques for analysing SoS were evaluated and it was identified that Characterisation and description of SoS (Henshaw 2013), and System of Interest (SoI) (Kinder et al. 2012) could be applied to the research. Characterisation of SoS allowed the boundaries and goals, terms and definitions and consequences of interactions to be fully understood, whereas SoI described the capabilities and functions of the constituents systems in order to ensure interoperability. The concept demonstrator that was considered as a SoS consisted of the integration of the assistive technologies that were reviewed to determine suitability. Powerchairs were the first area to investigate to establish the different types that were commercially available to assist users with reduced physical ability, ranging from standard powerchairs to those controlled using voice and EEG signals. This provided an understanding of how the technologies to be recommended by the framework would need to integrate into a powerchair. ATRS and SmartATRS were investigated to fully understand the system architectures to enable additional technologies to be integrated through the feasibility trials. The forms of technology to be evaluated were elicited by reviews of online sources and journal papers and consisted of EEG using an actiCAP (Brain Products 2017), Tracking Learning Detection, iOS Switch Control (Apple Inc. 2016) and smartglasses in the form of a Recon Jet (Recon Instruments 2017).

The final phase of the literature review concerned the industrial development models that were relevant to the framework development and exploitation. The Capability Maturity Model (Paulk et al. 1993) was found to be applicable in that a Level 1 organisation without a background in the domain developed the framework but it would need to be exploited by Level 3 organisations in the assistive technology domain.

The performed state of art review satisfied Objective 1 by analysing the domains that would be relevant to research.

11.1.3 Objective 2: User and Manufacturer Requirements

Objective 2 was satisfied by performing a two-phase requirements elicitation process involving users with reduced physical abilities and an assistive technology manufacturer.

The user group of people with reduced physical ability was established by approaching disability organisations with an online survey and visiting the Victoria Education Centre to conduct semi-structured interviews. The interviews were based on the survey questions to form the user requirements in terms of the challenges that were encountered in the participants' daily lives and their views on technologies that could potentially improve their Quality of Life. The findings highlighted the activities that needed significant physical effort to be exerted were the most challenging such as opening/closing doors and windows, as well as operating appliances that either had small dials or generated heat. In terms of outdoor tasks, using public transport, staying in overnight accommodation and operating a powerchair in the rain or snow produced greatest difficulties. The final section of the survey identified that touch, head and eye interactions would potentially be the most useful forms of technology; thus providing the directions for the feasibility trials.

The manufacturer requirements were elicited through collaboration with Dynamic Controls who produced the requirements specification provided in Appendix F. This was converted into a series of atomic functional and non-functional Volere Requirements in relation to technologies and the framework (Appendix G), which were defined in Requirement Shells (Robertson and Robertson 2006). The non-functional requirements concerned the reliability, interoperability, safety and usability of technologies, which provided further aspects to assess during the feasibility trials and controlled usability evaluations. It is acknowledged that a limitation was that only one company was approached to elicit manufacturer requirements when there are other suitable assistive technology industries. Future developments of the SmartAbility Framework would need to involve collaboration with multiple industries.

The outputs of the requirements elicitation phase have been published in the EHF 2015 conference paper.

11.1.4 Objective 3: Trials and Evaluations

The third objective was realised through the conduction of five feasibility trials and three controlled usability evaluations.

The first feasibility trial was centred on investigating the use of EEG as a modality of interaction via brain signals. An actiCAP was used for the trial that involved a 35-minute preparation process to attach the actiCAP to the head of the participant and administer a sand-based gel to ensure good electrode connections. This was an initial disadvantage of the technology as this would not be practical in a real world situation. The trial ascertained the movements that resulted in reliable fluctuations in brain activity and concluded that eye and tongue movements, winking, smiling and speaking certain commands would be suitable. However, due to the obtrusive nature of the technology it was determined not to be suitable as an interaction modality. Feasibility Trial 2 assessed whether Tracking-Learning-Detection (TLD) 1.0 to be utilised as a form of facial feature tracking with a smartphone. Through conduction of the tutorials, it was established that the technology could accurately track the nose on a Windows computer, however as TLD 1.0 required the MATLAB environment, a smartphone implementation of the algorithm would not be feasible. The next feasibility trial assessed the second generation of the algorithm, TLD 2.0, which had the advantage of being a Windows executable application that did not require MATLAB. The performance of the algorithm was seen to be improved as tracking was resumed more effectively when an object re-entered the field of view than TLD 1.0. TLD provided an interesting form of interaction however, as a smartphone implementation required C++ programming knowledge that the author did not possess, alternative technologies were investigated. The fourth feasibility trial was centred on iOS Switch Control as a method of interacting via head movements. The advantage of technology being that it was an existing accessibility feature of the iOS operating system and therefore required no additional application development, unlike TLD. The two operating modes of Switch Control were evaluated through general iOS navigation and selection commands, and with the SmartATRS user interface. Although both modes could be used, it was found that Point Mode provided a most efficient form of interaction that required less physical effort than Item Mode. However the usability of Item Mode could be improved by enabling the Auto Scanning feature that reduced the number of head movements required. The final feasibility trial established whether a Recon Jet smartglass could be used as an assistive technology. In order for the smartglass to be used with SmartATRS, an alternative user interface was developed that could be visible on the small display and responded to the button presses and touchpad movements on the device. Once the interface was developed, SmartATRS could be used on the device, albeit with a small display. As the technologies investigated in Trials 4 and 5 could successfully operate SmartATRS, it was decided that controlled usability evaluations should be conducted.

The first evaluation compared the usability of keyfob, touch and joystick-based interactions by a user group who control the ATRS installed in the vehicle of the author. The evaluation utilised System Usability Scale (SUS) and NASA Task Load Index (TLX) to measure the usability and enable comparisons to be made. Overall, it was concluded that touch-based interaction was the most usable, keyfobs had small buttons that required significant finger dexterity and joystick interaction had a steeper learning curve due to the coordination required to simultaneously operate the joystick and observe the smartphone display. The emergency stop feature of SmartATRS was seen to improve the safety of ATRS as all functions could be terminated instantly with a single button press compared to the keyfobs that required functions to be terminated individually. As a result of the risks identified with utilising a vehicle in an outdoor environment for Evaluation 1, the second evaluation was conducted with a simulation of SmartATRS with video clips to illustrate each function. The evaluation was performed with the same procedure as Evaluation 1, whereby SUS and NASA TLX were applied to compare the usability of touch and head-based interactions. The results show that touch interaction achieved 'Good Usability' and head interaction only achieved 'Poor Usability' according to the Adjective Rating Scale (Bangor et al. 2009). This was due to most participants not possessing the required 80˚ neck ROM for iOS Switch Control to detect the head movements. Evaluation 3 investigate the usability of smartglasses with participants at the 2016 Mobility Roadshow by applying the simulation of SmartATRS. The challenges of the Recon Jet highlighted in the feasibility trial led to the evaluation not being conducted as a full controlled usability evaluation with questionnaires. Most participants could not use the smartglasses, either because of insufficient dexterity or visual acuity.

The outputs of the technology trials and evaluations have been published in conference papers including PECCS 2015 and SoSE 2015.

11.2 Critical Evaluation of the Research

The research results have been previously critically evaluated in Chapter 4 to Chapter 9 in alignment to the contributions to knowledge defined in Chapter 1. The following provides further critical evaluation of the research phases in order to maximise the potential for future recommendations of research.

Requirements Elicitation

The elicitation of user requirements provided useful insights into the challenges that people with reduced physical ability currently encounter in their daily lives. The user group consisted of 16 participants, which is a relatively small sample size for research. However, the user community was considered to be niche as it was necessary for respondents to have reduced physical ability whilst having the cognitive competence to answer the survey/interview questions. A larger sample size could have provided additional challenges and technology preferences to contribute to directions of the feasibility trials. Only Victoria Education Centre was utilised for the semi-structured interviews due to the convenience of being a local special educational needs school. There were similar institutions that could potentially be suitable but were at a greater geographical distance from the author. By conducting the research, it has been realised that there are other technologies that could have been suggested to the user group in the final section of the survey.

The manufacturer requirements from Dynamic Controls was instrumental in providing the characteristics to consider when evaluation technologies during the feasibility trials. The adoption of Volere enabled clearly-defined atomic requirements to be established using Requirement Shells (Robertson and Robertson 2009). It is acknowledged that only one manufacturer was involved during the process, however Dynamic Controls have a global market in powerchair controllers. Alternative companies could have been approached to elicit additional manufacturer requirements.

Feasibility Trials

Five feasibility trials were conducted to determine the directions for the controlled usability evaluations. It is acknowledged that having the author conducting the trials independently could be viewed as a limitation due to the decisions of suitability being based on a single participant who had reduced physical ability. As this was an initial exploratory stage of the research and due to the complex logistics of the trials, it was not efficient to involve multiple participants at this stage. The results of these trials were underpinned in the controlled usability evaluations that were conducted by other participants.

Trial 1 obtained the actions that resulted in detectable fluctuations in brain activity and those that were not suitable. The actiCAP product used in the trial had a time-consuming preparation procedure that was considered impractical for people with reduced physical ability, hence determining that the EEG technology would not be investigated further. It is realised that alternative EEG technologies could provide increased usability and therefore be suitable assistive technologies that could be evaluated as a future direction. Trial 2 established the capabilities of the TLD 1.0 algorithm, which enabled the technology to be classed as a potential alternative interaction method. The third feasibility trial investigated the second generation of TLD and successfully established that the performance of the algorithm had been improved on a Windows PC. However, a smartphone implementation of TLD 2.0 could not be achieved due to insufficient C++ programming knowledge of the author. This led to an inconclusive evaluation of the technology as the feasibility could not be determined, but TLD was considered as an interesting technology to be investigated in future research. Trial 4 was successful in establishing that iOS Switch Control could provide an alternative interaction modality for SmartATRS. Through comparing the usability of each Switch Control operating mode to navigate through iOS and SmartATRS, a finding could be obtained that Point Mode was the most efficient through requiring a minimal number of head movements for navigation and selection, although Item Mode could be more usable for some physical conditions. However, Switch Control only provided a solution for operating iOS through head movements, as the technology was not compatible with other operating systems. The final feasibility trial evaluated smartglass interaction through the Recon Jet and by producing an alternative interface for SmartATRS, the trial effectively determined that the Recon Jet provided an alternative modality. The Recon Jet was the only product to be trialled due to affordability; trials of alternative products could be conducted in the future that may offer increased usability of smartglasses.

SoS Characterisation and Description

Prior to the conduction of the controlled usability evaluations with the SmartPowerchair concept demonstrator, analysing the demonstrator as a System of Systems (SoS) provided a clear understanding of the constituent systems. The knowledge obtained enabled a Hierarchical Task Analysis (HTA) to be implemented that informed the structure for evaluations, in terms of instructions provided to the participants who had no prior experience of operating SmartATRS. As the SmartPowerchair relied upon the interactions between a number of constituent systems, the adoption of Characterisation of SoS (Henshaw et al. 2013) enabled the capabilities and function services to be determined. To supplement this, System of Interest (SoI) analysed the lifecycle that would need to be considered for a SmartPowerchair. SoI was useful in highlighting the phases that would need to be performed from Concept to Disposal in terms of Capability, SoS, Systems, Component and Technology Development. Of particular relevance was the exploitation methods that should be ascertained such as utilisation by the intended user community. The analyses from Characterisation of SoS and SoI were combined to provide a detailed comprehension of the concept demonstrator. The concept of interoperability of SoS was demonstrated by a rear view camera that was integrated with a powerchair and smartphone or tablet to assist with manoeuvring. To supplement the research, the concept demonstrator was applied to the RASoS initiative to calculate risk in a SoS. RASoS did not provide a key contribution to this research and was not validated by an application to another case study or involvement of domain experts. Such activities could be considered as future work.

Controlled Usability Evaluations

The first controlled usability evaluation compared interaction using keyfobs, touch and joystick based and identified that touch-based was the most usable, keyfobs were challenging due to small buttons and joystick had a steep learning curve due to the required coordination. A significant limitation of this evaluation was that able-bodied participants were used rather than participants with reduced physical abilities. This was because collaboration had not been established with the user community at the time of conducting the evaluation. It is anticipated that using the intended user group would have varied the results. The evaluation could have been further improved by varying the order of the task performed to avoid an identical learning curve between participants, e.g. keyfobs could be seen as the most challenging modality as this was the first time the participants interacted with ATRS. Performing the evaluation in an outdoor environment involving a vehicle and the ATRS components created notable risks to both the participants and author. The second evaluation addressed these limitations by using participants with reduced physical ability, developing a simulation (consisting of video clips) that could be performed in an indoor environment to avoid the use of a vehicle and ATRS, and alternating the order in which the participants completed the tasks. Evaluation 2 was successful in finding that Range of Movement (ROM) was a key determinant as to whether the user could operate a head interaction. This formed the basis of the established framework. The final controlled usability evaluation also used simulation and participants were established through attendance at the 2016 Mobility Roadshow. However, this evaluation was not conducted as a full controlled usability evaluation due to challenges identified with the Recon Jet during the feasibility trial and therefore, it was not possible to generate direct SUS and NASA TLX comparisons with Evaluations 1 and 2. Nevertheless, Evaluation 3 highlighted that the Recon Jet would not be suitable as an assistive technology. It could be argued that alternative methods of measuring usability could have been applied instead of SUS and NASA TLX, such as the Subjective Workload Dominance Technique (Stanton et al. 2013, p.300-315). However, these were not selected as they are well-established methods for analysing the workload of users having the advantage of providing an efficient means of estimating workload with a minimal amount of training required (Stanton et al. 2013, p.315-320). However, the results from the three evaluations allowed knowledge to be generated which was incorporated into the SmartAbility Framework.

Framework Development

The initial version of the framework (SmartDisability) was developed based on the original conceptual model that was derived on research findings. Six elements were created, which could efficiently be aligned to the internationally-recognised Disability symbol to form a new conceptual model. The framework was subsequently validated through the user community at the 2016 Mobility Roadshow and technology and healthcare domain experts in the focus group. The two-phased validation approach was effective at obtaining valuable feedback from a range of different viewpoints. The validation at the Mobility Roadshow was performed via a paper-based method whereby a spreadsheet was completed to record the abilities of participants. With hindsight, this was not an effective method of recording data, as difficulties were encountered with illegible handwriting, space restrictions and the capability to capture their views within a limited timeframe. A lesson learnt was that electronic data capture methods should be adopted in future where possible. However, the focus group of domain experts operated efficiently and adhered to the two-hour duration. There were no conflicting interests within the experts and valuable group discussions were achieved. In both phases, questionnaires provided informative feedback on the SmartDisability Framework, where a number of key limitations were identified. Most notably, the term 'disability' was perceived as having a negative connotation and the mappings within the framework were seen to be too simplistic. This negative connotation had not been considered during the development of the framework. The second version of the framework (known as 'SmartAbility') was subsequently developed and addressed all suggested limitations. The mappings were enhanced through the efficient adoption of the Quality Function Deployment (QFD) tool that enabled symbols and colour codes to be derived and the subsequent creation of a House of Quality (HoQ) model to describe the framework. Healthcare and technology domain experts were instrumental in supplementing the framework with additional physical conditions and technologies respectively. A participant commented that the framework did not account for combinations of abilities, as each was considered individually (i.e. lifting the shoulder and bending the elbow) and this could lead to additional recommendations being made. It was acknowledged that this was a limitation of the framework, which could be considered in future developments. Version 3 of the framework and HoQ model was re-validated with domain experts with semi-structured interviews. The feedback from this phase was generally positive and minor enhancements were elicited such as additional physical conditions to be incorporated. This demonstrated that the iterative developments of the framework was vital to improve the accuracy of the framework. Performing a two-phased validation process resulted in a final consolidated SmartAbility Framework being successfully developed that was suitable for exploitation to achieve the research aim. However, it will be possible to further enhance the framework through the incorporation of additional technologies and update existing content. This will ensure that the framework remains suitable for assistive technology domains and continue to provide a suitable recommendations to the user community. It is recognised that the framework does not consider the cognitive abilities of users, which was a category identified by the Downton Scale (Andrews 2014) and could be a significant determining factor for suitable technologies. Cognitive ability could be incorporated by conducting a review of the different types and suitable measurement techniques.

11.3 Industry and Future Research Recommendations

Based on the knowledge and results obtained during the research, the following recommendations and suggestions of future directions have been derived. These are classified in accordance with the key stakeholders identified for research as described in section 1.3. These include people with reduced physical ability, special educational institutions (e.g. Victoria Education Centre), residential homes (e.g. Talbot Manor), assistive technology manufacturers (e.g. Dynamic Controls) and the healthcare domain.

11.3.1 Recommendations

People with reduced physical ability

- The user community should increase their awareness of currently-available technologies that can support and improve their quality of life through utilisation of the exploited SmartAbility Framework. The importance of promoting technologies has been acknowledged by Ari et al. (2010).
- Technologies should be utilised by people with reduced physical ability that enable tasks to be performed independently without the exertion of significant physical effort or external support. This should be achieved through

the inputting of their abilities into the SmartAbility Framework in order for suitable technology recommendations to be made.

- Quality of Life in terms of Practical Becoming (Ontario Adult Autism 2016) should be improved through adoption of the technologies recommended by the SmartAbility Framework. This is anticipated to be realised through an increase in the number of daily activities that the users can perform independently.

Special Educational Institutions/Residential Homes

- A view shared by the validation participants and endorsed by the author is that institutions should focus on the positive aspects of people's abilities rather than the negative. From the author's personal experience, this is not often the case and positive terminology should be promoted to foster greater awareness.

- Employees should therefore be encouraged to adopt alternative terminology when referring to 'disability', 'impairment', and 'limitations'. Despite these terms being considered politically correct, the user community has viewed them as having negative connotations which was identified during the research. The term 'reduced physical ability' should be utilised as an alternative. Similarly, 'reduced mental ability' should be adopted when describing people with mental conditions.

Manufacturers

- Awareness should be promoted that physical conditions (i.e. disabilities) are not a determinant for technology suitability, as there are varying types that result in unique abilities. The abilities of individual users presents a greater indication, as demonstrated by the SmartAbility Framework.

- Manufacturers of technologies should consider the suitability of using their products as assistive technologies. An example of this was the smartglasses that could be exploited in an additional market.

- The risk implications of assistive technologies should be studied during the development as identified by the RASoS Initiative that could adversely affect the users' experience when interacting with technologies.

- The possibilities of integrating existing 'off-the-shelf' technologies into existing assistive technologies should be explored to ascertain viable solutions to aid people with reduced physical ability. An example of such an integration performed during the research was the rear view camera (Rear View Safety Inc. 2017) into a standard powerchair to support navigation.

- Assistive technology products should be advertised and promoted through the SmartAbility Framework.

Healthcare Domain

- Patients in rehabilitation (e.g. head and spinal injuries), paediatrics and orthotics should utilise the SmartAbility

Framework to obtain technology recommendations that could provide assistance in their daily lives.

- Allied Health Professionals (i.e. Occupational Therapists, Physiotherapists and Speech and Language Therapists), General Practitioners and Disabled Living Centres should adopt the SmartAbility Framework to assist, advise and inform their clients.

- The SmartAbility Framework should be promoted at healthcare-related exhibitions and conferences, e.g. Rehab Week (Kenes International 2017), the OT Show (CloserStill Media 2017) and the NAIDEX exhibition (Prysm Ndex Ltd. 2017).

11.3.2 Future Research

Feasibility Trials

- To investigate alternative forms of EEG technology and ascertain whether there are products that are more usable than the actiCAP and require a reduced amount of preparation time. An example of one technology that could be the subject of a future feasibility trial is the EMOTIV Epoc+ EEG headset (EMOTIV Inc. 2017) that appears to have the advantage of being less obtrusive as gel does not need to be administered. The purchased cost of the project is significantly less than the actiCAP, however as the Emotiv EPOC has 16 electrodes compared to 64 electrodes on the actiCAP, the data obtained would be less extensive.

- To explore the TLD algorithm further and determine whether an implementation on a smartphone platform can be achieved to provide a means to interact with the device through facial features. This would involve training in C++ programming in order to elicit the required knowledge.

- To ascertain whether there are technologies that provide the capability of head interaction with Android and other smartphone operating systems, similar to iOS Switch Control. This would ensure that the head-based interaction recommendation provided by the SmartAbility Framework is not dependent on a specific operating system.

- As the requirements elicitation highlighted that navigating powerchairs indoors was challenging due to narrow doors, research could be conducted to ascertain the feasibility of developing an obstacle avoidance system. The system would need to detect the edges of doors and prevent the powerchair from collisions by intercepting commands received from the joystick controller. The obstacle detection could be achieved through utilising a time-of-flight distance sensor attached to the powerchair that measures the time taken for the emitted laser source to refract back to the sensor from the surroundings (Adafruit 2017), e.g. door frames.

- To continuously review the technology market to identify whether there are alternative new technologies being developed that could be evaluated in future feasibility trials and controlled usability evaluations.

SmartAbility Framework

- Address the validations feedback classified as future work in Appendix R by implementing the necessary modifications to the SmartAbility Framework, in particular:
    - Incorporation of muscle movement sensors to the Technologies element.
    - Considering up and down tongue movements as alternative modalities of interaction.
    - Investigating whether combinations of abilities could be used to produce alternative interaction medium and technology recommendations.
    - Including technologies that have more than one input type to increase the range of technologies within the framework.

    - Ascertaining whether the symbols adopted from QFD comply to standardised learnability guidelines (Grossman et al. 2009) in order to improve usability.
    - Considering incorporation of cognitive ability as an alternative determinate for interaction mediums and technologies.
- Develop a smartphone application for the SmartAbility Framework that enables users with physical conditions to input their abilities and obtain recommendations of suitable interaction mediums and technologies. The application should be developed to accurately portray the knowledge and mappings within the framework. The images included in the Abilities, Interaction Mediums and Technologies elements of the framework should be incorporated into the application to assist with user input. The produced recommendations would also need to provide descriptions and external website hyperlinks to enable users to investigate the technologies further, which could result in potential purchase. To address a comment raised in the SmartAbility validation, a feature could be implemented that allows users to state that they have full or no function of each group of abilities. A prototype version of the application has been developed and screenshots of the input (Evaluation) and output (Recommendations) user interfaces are shown in Figure 70.

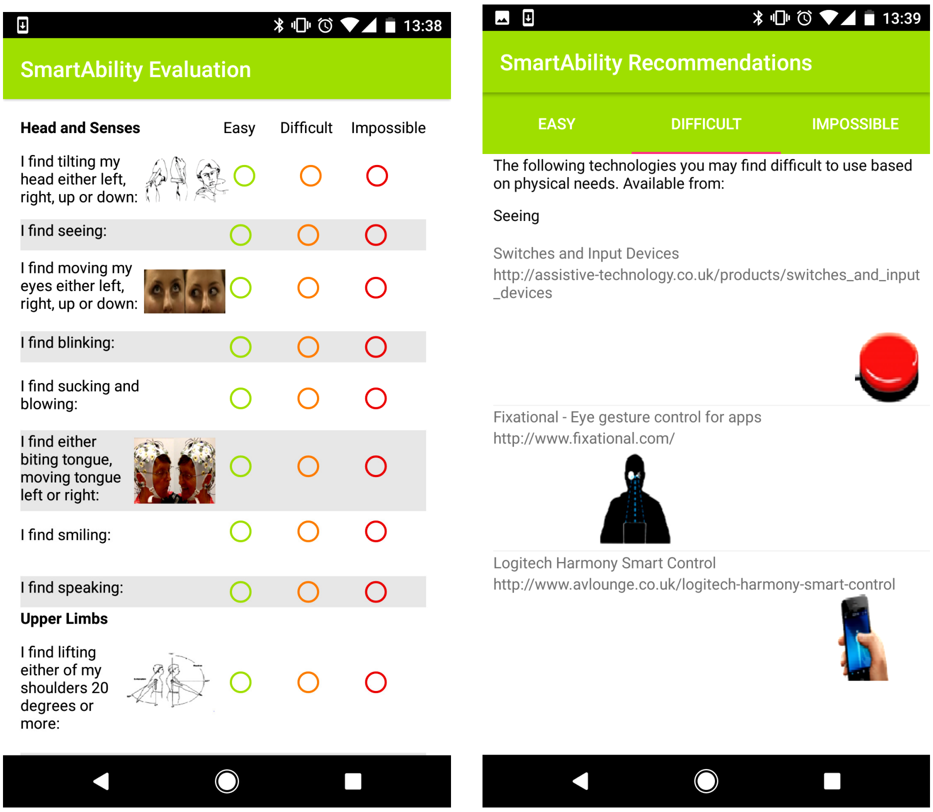


Figure 70: Input and output user interfaces of the prototype SmartAbility application

- Extend the application by incorporating automated input where the behaviour and abilities (e.g. eye and head movements) of the user are captured over a period of time. The application could then determine the actions that the user is able to perform and tasks that present challenges and suggest technologies to assist. Therefore, the application would not require manual input from the user which could be challenging due to reduced finger dexterity.

- Actively collaborate with further assistive technology industries to promote the SmartAbility applications as a method of recommending technologies to people with reduced physical ability. This could be achieved through demonstrations of the applications at consumer events such as the Mobility Roadshow, visits to assistive technology manufacturers and writing journal papers.

11.4 Summary

The aim and objectives have been realised through a number of outputs and resulting publications in conferences and journals from each research phase. The first objective analysed the relationship between reduced physical ability, HCI and SoS that was necessary to inform the structure of the developed frameworks. Eliciting user and manufacturer requirements to satisfy Objective 2 enabled an understanding of the current difficulties encountered by people with reduced physical ability and the interests in technology from the user community. To meet Objective 3, a series of feasibility trials were performed to ascertain which technologies have the potential to improve Quality of Life and controlled usability evaluations measured the extent to which the technologies would be suitable. The SmartDisability and subsequent SmartAbility Frameworks were developed to reflect the mappings between disability type and technology based on the prior knowledge obtained, which were validated through the involvement of the user community and domain experts. This represents the key contribution to knowledge of the research. A critical evaluation of the research phases highlighted the successful aspects and provided suggestions for improvement. The concluding statements provided recommendations for the assistive technology and areas of future research. The SmartAbility Framework therefore achieved the aim of the research by enhancing multimodal interaction for people with reduced physical ability.

References

Adafruit, 2017. *Adafruit VL53L0X Time of Flight Distance Sensor - ~30 to 1000mm.* [online]. New York, NY: Adafruit. Available from: https://www.adafruit.com/product/3317 [Accessed 27 March 2017].

Agoston, T., Ueda, T. and Nishimura, 2000. Pervasive computing in a networked world. *The 10th Annual Internet Society Conference*, Yokohama, 18-21 July 2000. 48-57. IEEE Press, New York, NY, USA.

Akao, Y., 1990, *Quality Function Deployment*. Cambridge, MA: Productivity Press.

Annett, J., 2003. Hierarchical Task Analysis. *In*: Hollnagel, E., ed. *Gandbook of Cognitive Task Design (Human Factors).* Mahwah, NJ: Lawrence Erlbaum Associates, 17-37.

Apple Inc., 2016. *iOS: Switch Control helps you navigate your iOS device* [online]. Cupertino, CA: Apple Inc. Available from: https://support.apple.com/en-gb/HT201370 [Accessed 12 December 2016].

Ari, I. A. and Inan, F. A., 2010. Assistive Technologies for Students with Disabilities: A Survey of Access and Use in Turkish Universities. *Turkish Online Journal of Educational Technology*, 9, 40-45.

Arthritis Research UK, 2016. *What is osteoarthritis?* [online]. Chesterfield: Arthritis Research UK. Available from: http://www.arthritisresearchuk.org/arthritis-information/conditions/osteoarthritis/what-is-osteoarthritis.aspx [Accessed 12 December 2016].

Atlantic Systems Guild, 2015. *VolereVolèreVolere (Voh-lair-ray) the Italian verb to want, or to wish.* [online]. London: Atlantic Systems Guild. Available from: http://www.volere.co.uk/index.htm [Accessed 12 February 2017].

Azani, C., 2009. *A Multi-criteria Decision Model for Migrating Legacy System Architectures into Open Systems and Systems-of-Systems Architectures*. Washington, WA: Defense Acquisition University.

Badcock, N.A., Preece, K.A., de Wit, B., Glenn, K., Fieder, N., Thie, J., and McArthur, G., 2015. Validation of the Emotiv EPOC EEG system for research quality auditory event-related potentials in children. *PeerJ*. 21, 524-534.

Bailey, M., Chanler, A., Maxwell, B., Micire, M., Tsui, K. and Yanco, H. 2007. Development of Vision-Based Navigation for a Robotic Wheelchair. *The IEEE 10th International Conference on Rehabilitation Robotics*, Noordwijk, Netherlands, 13-15 June 2007. IEEE Press, New York, NY, USA.

Barnard, M., Drey, N. and Bryson, C., 2012. *NSPCC Research Ethics Committee: Guidelines for Applicants* [online]. London: National Society for the Prevention of Cruelty to Children. Available from: https://www.nspcc.org.uk/globalassets/documents/evaluation-of-services/research-ethics-committee-guidance-applicants.pdf [Accessed 28 July 2017].

Barnes, C., 2014. Understanding disability and the importance of design for all. *Journal of Accessibility and Design for All*. 1 (1), 56-80.

Barot, V., Henson, S., Henshaw, M., Siemieniuch, C., Sinclair, M., Lim, S. L., Jamshidi, M and DeLaurentis, D., 2012. SoA Report

Beigl, M., Gellersen, H.W., and Schmidt, A., 2001. Mediacups: Experience with Design and Use of Computer- Augmented Everyday Objects. *The International Journal of Computer and Telecommunications Networking*. 35 (4), 401-409.

Bennet, S., Bishop, A., Dalgarno, B., Waycott, J. and Kennedy, G., 2012. Wireless Implementing Web 2.0 technologies in higher education: A collective case study. *Computers & Education*. 59, 524-534.

Bicevska, Z., 2009. Applying of Smart Technologies: Evaluation of Effectiveness. *Advances in Software Engineering Techniques*. 7054 (2012), 193-201.

Bloor, M., Frankland, J., Thomas, M. and Robson, K., 2000 *Focus Groups in Social Research*. London: Sage Publications.

Bobrov, P., Frolov, A., Cantor, C., Fedulova, I., Bakhnyan, M and Zhavoron A., 2011. Brain-Computer Interface Based on Generation of Visual Images. *PLoS One*. 6 (6).

Boehm, B. and Abts, C., 1999. COTS Integration: Plug and Pray? *Computer*. 32 (1), 135–138.

Bolt, R.A., 1980. “Put-that-there”: Voice and gesture at the graphics interface. *The 7th Annual Conference on Computer Graphics and Interactive Techniques*, Seattle, USA, 14-18 July 1980. 262-270. ACM Press, New York, NY, USA.

Borough of Poole, 2016. *Beach Accessibility* [online]. Poole: Borough of Poole. Available from: http://www.poole.gov.uk/leisure-andculture/beaches/advice-for-visitors/beach-accessibility/ [Accessed 7 December 2016].

Brain and Spine Foundation, 2013. *Motor neurone disease: a fact sheet for patients and carers* [online]. London: Brain and Spine Foundation. Available from: http://www.brainandspine.org.uk/sites/default/files/documents/BSF_motor_neurone_disease.pdf [Accessed 1 March 2017].

Brain Products GmbH., 2017. *actiCAP ControlSoftware* [online]. Gilching: Brain Products GmbH. Available from: http://www.brainproducts.com/downloads.php?kid=8 [Accessed 10 February 2017].

Brain Products GmbH., 2017a. *EEG* [online]. Gilching: Brain Products GmbH. Available from: http://www.brainproducts.com/products_by_apps.php?aid=5 [Accessed 12 February 2017].

Brain Products GmbH., 2017b. *Technical Specifications* [online]. Gilching: Brain Products GmbH. Available from: http://www.brainproducts.com/productdetails.php?id=4 [Accessed 12 February 2017].

Brain Vision UK, 2017. *The third generation of active electrodes* [online]. London: Brain Vision UK. Available from: http://brainvision.co.uk/acticap [Accessed 12 January 2017].

Briggs, P. and Little, L., 2009. Pervasive computing and disability: designing for independence? *The 2nd International Conference on PErvasive Technologies Related to Assistive Environments*, Corfu, Greece, 09-13 June 2009. 40. ACM Press, New York, NY, USA.

Britten, N., 2006. Qualiative interviews. *In:* Pope, C. and Mays, N., eds. *Qualitative research in healthcare*. 3rd edition. Oxford: Blackwell Publishing, 32-42.

Brooke, J., 1986. SUS: A "quick and dirty" usability scale. *In:* Jordan, P.W, Thomas, B., Weerdmeester, B.A. and McClelland, I.L., eds. *Usability evaluation in industry*. London: Taylor & Francis, 189-194.

Bryman, A., 2012. *Social research methods*. 5th edition. Oxford: Oxford University Press.

Buscemi, S., 2013. *iOS7 Control your iPhone or iPad with Head Movements* (iOS 7 new feature) [video, online]. YouTube. Available from: https https://www.youtube.com/watch?v=cdw4O4DM3wI [Accessed 5 December 2016].

Butler C., 1986. Effects of powered mobility on self-initiated behaviors of very young children with locomotor disability. *Developmental Medicine and Child Neurology*. 28(3), 325–332

Caridakis, G., Asteriadis, S., Karpouzis K., 2011. Non-manual cues in automatic sign language recognition. *The 4th International Conference on PErvasive Technologies Related to Assistive Environments*, Crete, Greece, 25-27 May 2011. 43. ACM Press, New York, NY, USA.

Carter, J., 2012. *How smarter cars and digital cities are about to change the way we drive* [online]. Bath: Future Publishing Ltd. Available from: http://www.techradar.com/news/car-tech/how-smarter-cars-and-digital-cities-are-about-to-change-the-way-we-drive-1090032 [Accessed 12 February 2017]

Central Statistics Office Ireland, 2010. *National Disability Survey 2006*, Volume 2. Dublin, Central Statistics Office Ireland.

Centre for Excellence in Universal Design, 2015. *What is Universal Design* [online]. National Disability Authority: Dublin. Available from: http://universaldesign.ie/What-is-Universal-Design [Accessed 12 February 2017].

Cheng, A., Auerbach, M., Hunt, E.A., Chang, T.P., Pusic, M., Nadkarni, V. and Kessler, D., 2014. Designing and conducting simulation-based research. *Pediatrics*. 133 (6), 1091-1101.

Clegg, D. and Barker, R., 1994. *Case Method Fast-Track: A Rad Approach*. Boston, MA: Addison-Wesley.

CloserStill Media, 2017. *The Occupational Therapy Show* [online]. London: CloserStill Media. Available from: http://www.theotshow.com/ [Accessed 7 April 2017].

Cofré, J.P., Moraga G., Rusu, C., Mercado, I., Inostroza, R. and Jiménez, C., 2012. Developing a Touchscreen-based Domotic Tool for Users With Motor Disabilities. *The 9th International Conference on Information Technology: New Generations*, Las Vegas, NV, USA, 16-18 April 2012. 696-701. IEEE Press, New York, NY, USA.

Collis, J. and Hussey, R., 2013. *Business Research: a practical guide for undergraduate and postgraduate students*. 4th edition. Basingstoke: Palgrave Macmillan.

Cortazar, B., Koydemir, H.C., Tseng, D., Feng, S. and Ozcan, A., 2015. Quantification of plant chlorophyll content using Google Glass. *Lab Chip*, 15 (7), 1708-1716.

Cowan, R.E., Fregly, B.J., Boninger, M.L., Chan, L., Rodgers, M.M. and Reinkensmeyer, D.J. 2012. Recent trends in assistive technology for mobility. *Journal of NeuroEngineering and Rehabilitation*. 9 (20), 1-8.

CS Health & Fitness, 2017. *Range of Motion – Should you always use it?* [online]. Bellshill: CS Health & Fitness. Available from: http://www.nhs.uk/Conditions/polio/Pages/Introduction.aspx [Accessed 12 January 2017].

Design For All Foundation, 2015. *Design for All is design tailored to human diversity* [online]. Barcelona: Design For All Foundation. Available from: http://designforall.org/design.php [Accessed 12 February 2017].

Devivo, M.J. 2012., Epidemiology of traumatic spinal cord injury: trends and future implications. *Spinal Cord.* 50(5), 365-372.

Disabled World, 2016a. *Disability: Definition, Types & Models* [online]. Disabled World: New York. Available from: https://www.disabled-world.com/definitions/disability-disabled.php [Accessed 17 November 2016].

Disabled World, 2016b. *Definition: Defining the Meaning of Electric Wheelchairs* [online]. Disabled World: New York. Available from: https://www.disabled-world.com/assistivedevices/mobility/wheelchairs/electric/ [Accessed 17 November 2016].

Dynamic Controls, 2015b. *iPortal – Dynamic Controls* [online]. Christchurch: Dynamic Controls. Available from: http://dynamiccontrols.com/en/iportal [Accessed 12 February 2017].

Dynamic Controls, 2017. *Home – Dynamic Controls* [online]. Christchurch: Dynamic Controls. Available from: http://dynamiccontrols.com/en/ [Accessed 10 February 2017].

Edugyan, A., 2013. *Fitness Assessment for Personal Training Services* [online]. Santa Monica, CA: Livestrong. Available from: http://www.livestrong.com/article/338717-fitness-assessment-for-personal-training-services/ [Accessed 23 November 2016].

Elder, S. and Vakaloudis, A., 2015. A technical evaluation of devices for smart glasses applications. *The Sixth International Conference on Internet Technologies & Application*, Wrexham, UK, 8-11 September 2015. IEEE Press, New York, NY, USA.

EMOTIV Inc., 2017. *EMOTIV Epoc - 14 Channel Wireless EEG Headset* [online]. San Francisco, CA: EMOTIV Inc. Available from: https://www.emotiv.com/epoc/ [Accessed 24 March 2017].

Engel, A., 2010. *Verification, Validation, and Testing of Engineered Systems*. Hoboken, NJ: John Wiley & Sons.

Epstein, S. Missimer, E. and Betke, M., 2014. Using kernels for a video-based mouse-replacement interface. *Personal and Ubiquitous Computing*. 18 (1), 47-60.

Ergonomic Seating Solutions, 2016. *Opera Chairs* [online]. Leyland: Ergonomic Seating Solutions. Available from: https://ergosol.co.uk/products.htm [Accessed 5 December 2016].

European Institute for Design and Disability, 2009. *The EIDD Stockholm Declaration 2004*. Dublin: European Institute for Design and Disability. Available from: http://www.designforalleurope.org/Design-for-All/EIDD-Documents/Stockholm-Declaration/ [Accessed 12 February 2017].

Feilzer, M. Y., 2010. Doing mixed methods research pragmatically: Implications for the rediscovery of pragmatism as a research paradigm. *Journal of Mixed Methods Research*, 4 (1), 6-16.

Fitzsimmons, M., 2014. *Samsung Smart Home platform brings connected home under one app's roof* [online]. Bath: Future Publishing Ltd. Available from: http://www.techradar.com/news/phone-and-communications/mobile-phones/samsung-smart-home-platform-brings-the-connected-home-under-one-app-s-roof-1212140 [Accessed 12 February 2017].

Flick, U., 2011. *Introducing research methodology: A beginner's guide to doing a research project.* London: Sage.

Francescutti C, Frattura L, Troiano R, Gongolo F, Martinuzzi A, Sala M, Meucci P, Raggi A, Russo E, Buffoni M, Gorini G, Conclave M, Pietrangeli A, Solipaca A, Leonardi M., 2009. Towards a common disability assessment framework: theoretical and methodological issues for providing public services and benefits using ICF. *Disabil Rehabil*. 31 (1), 8-15.

Fuller M., 2015. *Recon Jet Smart Eyewear Aims To Be Sports Version Of Useful Google Glass* [online]. SportTechie. Available from: http://www.sporttechie.com/2015/04/16/gadgets/recon-jet-smart-eyewear-aims-to-be-sports-version-of-useful-google-glass/ [Accessed 12 January 2017].

Gaba, S.G., Singh, P. and S.K. Arora, 2016. Electronic Wheelchair for Physically Disabled Persons. *Indian Journal of Science & Technology*, 9 (21), 1-7.

Gallagher, B. and Petrie, H., 2013. Initial Results from a Critical Review of Research for Older and People with disability. *The 15th ACM SIGACCESS International Conference on Computers and Accessibility*, Bellevue, Washington, WA, USA, 21-23 October 2013, 53 ACM Press, New York, NY, USA.

Gao, A., Miller, T., Spletzer, J.R., Hoffman, I. and Panzarella, T., 2008. Autonomous docking of a smart wheelchair for the Automated Transport and Retrieval System (ATRS). *Journal of Field Robotics*, 25 (4-5), 203-222.

Gerald Simonds Healthcare Ltd., 2017. *TDX SP* [online]. Aylesbury: Gerald Simonds. Available from: http://www.ilearn.com/isupportcollege/Help_Guides/LMS_Help Guide.html [Accessed 12 January 2017].

Gill, P., Stewart, K., Treasure, E. and Chadwick, B., 2008. Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal*, 204, 291-295.

Goddard, W. & Melville, S., 2004. *Research Methodology: An Introduction*. 2nd edition. Oxford: Blackwell Publishing .

Google Inc., 2016. *Design before you develop* [online]. Mountain View, CA: Google Inc. Available from: https://developers.google.com/glass/ [Accessed 12 December 2016].

Gosling, A., 2014. *Welcome to the Bournemouth University EEG lab* [online]. Poole: Bournemouth University. Available from: http://angelagosling.wordpress.com/ [Accessed 12 February 2017].

GOV.UK, 2006. *Age Legislation Fact Sheet No.2: Objective Justification* [online]. Kew: The National Archives. Available from: http://webarchive.nationalarchives.gov.uk/20060715185623/dti.gov.uk/files/file29240.pdf [Accessed 7 December 2016].

GOV.UK, 2014. *Inclusive language: words to use and avoid when writing about disability* [online]. London: GOV.UK. Available from: https://www.gov.uk/government/publications/inclusive-communication/inclusive-language-words-to-use-and-avoid-when-writing-about-disability [Accessed 28 February 2017].

Government Equalities Office, 2010. *Equality Act 2010: What you need to know? Disability Quick Start Guide* [online]. London: Government Equalities Office. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/85011/disability.pdf [Accessed 12 January 2017].

Grossman, T., Fitzmaurice, G. and Attar, R., 2009. A Survey of Software Learnability: Metrics, Methodologies and Guidelines. *SIGCHI Conference on Human Factors in Computing Systems*, Boston, MA, USA, 4-9 April 2009. 649-658. ACM Press, New York, NY, USA.

Guevara, J.A., 2011. *Focus Group Basic Rules* [online]. Allendale, MI: Grand Valley State University. Available from: https://www.gvsu.edu/cms3/assets/B8AD748B-F1BE-C0A8-A2463EB026FEEEFD/focus_groups_2_14_11.pdf [Accessed 28 February 2017].

Halpern-Manners, A. and Warren, J.R., 2012. Panel Conditioning in Longitudinal Studies: Evidence from Labor Force Items in the Current Population Survey. *Demography*, 49 (4), 1499-1519.

Harding, A., Mollett, J. and Touchin, M., 2009. A structured approach to planning and managing systems engineering capability evolution in a complex through-life business space. *The 7th Annual Conference on Systems Engineering Research*, Singapore, 20-23 July 2009. 3-5. Wiley Online Library, Hoboken, NJ, USA.

Headway, 2011. *What is an Acquired Brain Injury?* [online]. Dublin: Headway. Available from:

http://www.headway.ie/download/pdf/what_is_abi.pdf [Accessed 12 February 2017].

Henshaw, M., 2013. *The Systems of Systems Engineering Strategic Research Agenda*. Loughborough: Loughborough University. Report TAREA-PU-WP5-R-LU-26.

Henshaw, M., Baker, S, Carter, J., Colby, S., Cooper, R. Dickerson, C. Drawbridge, N., Evans, C., Fagg, J., Hart, S., Haywood-Evans, R., Hobbs, J., Huggett, D., Kinder, A., Morua, M., Pearce, D., Rabbets, T., Siemieniuch, C., Sinclair, K., Spencer, J. and Tutt, S., 2011. *Assessment of open architectures within defence procurement issue 1: systems of systems approach community forum working group 1 - open systems and architectures* [online]. Loughborough: Loughborough University.

Hicks, S.L., Wilson, I., Muhammed, L., Worsfold, J., Downes, S.M. and Kennard, C., 2013. A depth-based head- mounted visual display to aid navigation in partially sighted individuals. *PLoS ONE*. 8, e67695.

Hill, N.J., Gupta, D., Brunner, P., Gunduz, A., Adamo, M.A, Ritaccio, A and Schalk, G., 2012. Recording human electrocorticographic (ECoG) signals for neuroscientific research and real-time functional cortical mapping. *Journal of Visualized Experiments*. 64 (e3993), 1-5.

Hills, C., 2014. In*tersection: A Dream Come True* [video, online]. YouTube. Available from: https://www.youtube.com/watch?v=1AfbGQ2DYjg [Accessed 5 December 2016].

Hitchins, D., 2009. *System of Systems - The Ultimate Tautology* [online]. Available from: http://www.hitchins.net/profs-stuff/profs-blog/system-of-systems---the.html [Accessed 2 December 2016].

Hornsby, P, 2010. *Hierarchical Task Analysis* [online]. UXmatters. Available from: http://www.uxmatters.com/mt/archives/2010/02/hierarchical-task-analysis.php [Accessed 17 November 2016].

Hull, E., Jackson, K. and Dick, J., 2011. *Requirements Engineering*. 3rd edition. London: Springer.

Human-Computer Interaction Lab, 2016. *QUIS: Questionnaire for User Interaction Satisfaction* [online]. College Park, MD: University of Maryland. Available from: http://www.lap.umd.edu/QUIS/index.html [Accessed 12 December 2016].

iLearn Inc., 2017. *Management (LMS)* [online]. Marietta, GA: iLearn Inc.. Available from: http://www.ilearn.com/isupportcollege/Help_Guides/LMS_Help Guide.html [Accessed 12 January 2017].

Innovator's Guide Switzerland, 2013. *Design Thinking – eine kurze Einführung* [online]. 27 February 2013. Available from: http://innovators-guide.ch/2013/02/design-thinking-2/ [Accessed 12 April 2017].

International Organization for Standardization, 2010. ISO 9241-210:2010 *Ergonomics of human-system interaction -- Part 210: Human-centred design for interactive systems* [online]. Geneva: International Organization for Standardization.

Iqbal, M.H., Aydin, A., Brunckhorst, O., Dasgupta, P. and Ahmed, K., 2016. A review of wearable technology in medicine. *Journal of the Royal Society of Medicine*, 109 (10), 372-380.

Iturrate, I., Antelis, J. and Minguez, J., 2009. Synchronous EEG Brain-Actuated Wheelchair with Automated Navigation. *The IEEE International Conference on Robotics and Automation*, Kobe, Japan, 12-17 May 2009. IEEE Press, New York, NY, USA.

Jadhav, D., Bhutkar, G., Mehta, V., 2013 Usability evaluation of messenger applications for Android phones using cognitive walkthrough. *The 11th Asia Pacific Conference on Computer Human Interaction*, Bangalore, India, 24-27 September 2013. 9-18. ACM Press, New York, NY, USA.

Jamshidi, M., 2009. *Systems of Systems Engineering – Innovations for the 21st Century*. Hoboken, NJ: John Wiley & Sons.

Kalal, Z., Mikolajczyk, K. and Matas, J., 2012. Tracking-Learning-Detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. 34 (7), 1409–1422.

Kalawsky, R.S., 2015. *Using architecture patterns to architect and analyze systems of systems* [online]. Loughborough: Loughborough University. Available from: http://www.lboro.ac.uk/research/avrrc/research/currentprojects/modellingandsimulation/using-architecture-patterns-to-architect-and-analyze-systems-of-systems-.html [Accessed 12 February 2017].

Kenes International, 2017. *REHABWEEK 2017: Translation and Clincial Delivery* [online]. Geneva: Kenes International. Available from: http://www.rehabweek.org/2017/Pages/default.aspx#.WOeBqPnyuUk [Accessed 7 April 2017].

Kielhofner, G., 2006. *Research in Occupational Therapy*. Philadelphia, PA: F.A. Davis Company.

Kleiner, K., 2008. *Robotic wheelchair docks like a spaceship* [online]. Waltham, MA: New Scientist. Available from: http://www.newscientist.com/article/dn13805-robotic-wheelchair-docks-like-a-spaceship.html [Accessed 12 February 2017].

Kostanjsek N., 2011. Use of The International Classification of Functioning, Disability and Health (ICF) as a conceptual framework and common language for disability statistics and health information systems. *BMC Public Health*. 1 (4), 1-6.

Kumar, R., 2014. *Research methodology: a step-by-step guide for beginners*. 4th editon. London: Sage Publications.

Kunze, K., Henze, N. and Kise, K. 2014 Wearable Computing for Older Adults – Initial Insights into Head-Mounted Display Usage. *The 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, Seattle, WA, USA, 13-17 September 2014. 83-86. ACM Press, New York, NY, USA.

Leggin, B. and Iannotti, J., 1999. Shoulder outcome measurement. *In:* Iannotti J.P. and Williams, G.R., eds. *Disorders of the shoulder: diagnosis and management*. Philadelphia, PA: Lippincott Williams & Wilkins, 1024-1040.

Leonardi, M., 2010. Measuring health and disability: supporting policy development. The European MHADIE project. *Disabil Rehabil*. 32 (1), 1-8.

Lippitt, S., Harryman D.T. and Matsen, F.A., 1993. *A practical tool for evaluating function: the simple shoulder test*. Rosemont, IL: American Academy of Orthopaedic Surgeons.

Livability, 2016a. *Victoria* [online]. London: Livability. Available from: http://www.victoria.poole.sch.uk/ [Accessed 21 December 2016].

Livability, 2016b. *Talbot Manor, Bournemouth* [online]. London: Livability. Available from: http://www.livability.org.uk/service/talbot-manor-bournemouth/ [Accessed 21 December 2016].

Lorenzi, L., 2015. *HCI (human-computer interaction) definition* [online]. Tech Target. Available from: http://searchsoftwarequality.techtarget.com/definition/HCI-human-computer-interaction [Accessed 12 February 2017].

Lowe, A.J., 2000. *Interactive Tutorial on the House of Quality Matrix.* [online]. Geneva: Webducate. Available from: http://www.webducate.net/qfd/qfd.html [Accessed 10 February 2017].

Maglogiannis, I., Betke, M., Pantziou, G. and Makedon, F., 2014. Assistive environments for the disabled and the senior citizens: theme issue of PETRA 2010 and 2011 conferences. *Personal and Ubiquitous Computing*. 18 (1), 1-3.

Maier, M. and Rechtin, E., 2002. *The Art of Systems Architecting*. 2nd edition. Boca Raton, FL: CRC Press.

Maier, M.W. 1998. Architecting Principles for Systems-of-Systems. *Systems Engineering.* 1 (4), 267-284.

Maithel, S.K., Villegas, L., Stylopoulos, N., Dawson, S. and Jones, D.B., 2005. Simulated laparoscopy using a head- mounted display vs traditional video monitor: an assessment of performance and muscle fatigue. *Surgical Endoscopy*. 19, 406–411.

Malu, M. and Findlater, L. 2014 "OK Glass?" A Preliminary Exploration of Google Glass for Persons with Upper Body Motor Impairments. *The 16th International AGM SIGACCESS Conference on Computers and Accessibility*, Rochester, NY, USA, 20-22 October 2014. 267-268. ACM Press, New York, NY, USA.

Marley, S., 2016. *The Importance and Effect of Sample Size* [online]. Exeter: Select Statistical Service. Available at: https://select-statistics.co.uk/blog/importance-effect-sample-size/ [Accessed 30 December 2016].

Marshall, A., Stanton, N.A., Young, M., Salmon, P.M., Harris, D., Demagalski, J., Waldmann, T., Dekker, S.W., 2003. *Development of the Human Error Template – a New Methodology for Assessing Design Induced Errors on Aircraft Flight Decks. Final Report of the ERRORPRED Project E! 1970 (August 2003*). London: Department of Trade and Industry.

Masala, C and Petretto D.R., 2008. From disablement to enablement: Conceptual models of disability in the 20th century. *Disability and Rehabilitation*. 30 (17), 1233-1244.

Metsis, V., Zhengyi, L., Lei, Y. and Makedon, F, 2008. Towards an Evaluation Framework for Assistive Technology Environments. *The 1st International Conference on PErvasive Technologies Related to Assistive Environments: proceedings of the 1st international conference on PErvasive Technologies Related to Assistive Environments*, Athens, Greece, 15-19 July 2008. 12. ACM Press, New York, NY, USA.

Meza, M., 2014. *What is Switch Control mode in iOS ?* [online]. Toronto: Komodo. Available from: http://gettecla.com/blogs/news/15538916-what-is-switch-control-mode-in-ios [Accessed 12 February 2017].

Microsoft Corporation, 2011. *Microsoft Flight* [online]. Seattle, WA: Microsoft Corporation. Available from: http://www.microsoft.com/games/flight/ [Accessed 31 December 2016].

Miles, M.B. and Huberman, M.A., 1994. *Qualitative Data Analysis: An Expanded Sourcebook*. 2nd edition. Beverly Hills, CA: Sage Publications.

Milhailidis, A., Elinas, P., Boger, J. and Hoey, J., 2007. An intelligent powered wheelchair to enable mobility of cognitively impaired older adults: an anticollision system. *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, 15 (1), 136-143.

Millar A., 2016. *The Reason Traffic Lights Are Red, Yellow, and Green* [online]. New York City, NY: Thrillist Media Group. Available from: https://www.thrillist.com/cars/nation/traffic-light-colors-history [Accessed 10 February 2017].

Miller, A., Malasig, J., Castro, B., Hanson, V.L., Nicolau, H. and Brandao, A. 2017 The Use of Smart Glasses for Lecture Comprehension by Deaf and Hard of Hearing Students. *The 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, Denver, CO, USA, 6-11 May 2017. 1909-1915. ACM Press, New York, NY, USA.

MND Association, 2017. *Brief guide to MND* [online]. Northampton: MND Association. Available from: http://www.mndassociation.org/what-is-mnd/brief-guide-to-mnd/ [Accessed 1 March 2017].

Mobility Choice, 2016. *Silverstone Mobility Roadshow 2016 – Getting Hands On With The Future Of Mobility* [online]. Camberley: Mobility

Choice. Available from: http://www.mobilityroadshow.co.uk/news/item/0/358/Silverstone-Mobility-Roadshow-2016-Getting-Hands-On-With-The-Future-Of-Mobility [Accessed 10 February 2016].

Mozilla Developer Network, 2017. *XMLHttpRequest* [online]. Mountain View, CA: Mozilla Corporation. Available from: https://developer.mozilla.org/en-US/docs/Web/API/XMLHttpRequest [Accessed 10 February 2017].

Muensterer, O., Lacher, M., Zoeller, C. and Kübler J., 2014. Google Glass In Pediatric Surgery: An Exploratory Study. *International Journal of Surgery*, 12 (4), 281-289.

Multiple Sclerosis Society, 2016. *What is MS* [online]. London: Multiple Sclerosis Society. Available from: http://www.mssociety.org.uk/what-is-ms/ [Accessed 12 December 2016].

Namduri, S., Yagnik, G., Ebaugh, D.D., Nagda, S., Ramsey, M.L., Williams, G.R. and Mehta, S., 2012. Defining functional shoulder range of motion for activities of daily living. *Journal of Shoulder and Elbow Surgery*. 21, 1177-1183.

National Aeronautics and Space Administration (NASA). *NASA TLX: Task Load Index* [online]. Washington, D.C.: National Aeronautics and Space Administration. Available at: https://humansystems.arc.nasa.gov/groups/tlx/ [Accessed 6 January 2017].

National Aeronautics and Space Administration, 1996. Nasa *Task Load Index (TLX) v. 1.0 Manual*. Washington, WA: National Aeronautics and Space Administration.

National Institute of Child Health & Human Development of the National Institutes of Health, 1993. *Research plan for the national centre for medical rehabilitation research*. Bethesda, MD: NIH Publication.

Neville, C., 2005. *Introduction to Research and Research Methods* [online]. Bradford : School of Management, University of Bradford. Available at: http://www.brad.ac.uk/acad/management/external/els/pdf/introductiontoresearch.pdf [Accessed 12 February 2017].

Newell, A.F, Gregor, P., Morgan, M., Pullin, G. and Macaulay, C., 2011. User-Sensitive Inclusive Design. *Universal Access in the Information Society*. 10 (3), 235-243.

Newsquest Media Group, 2004. *Hospital negligence led to boy's disability* [online]. High Wycombe: Newsquest Media Group. Available from: http://www.bournemouthecho.co.uk/news/5361248.Hospital_negligence_led_to_boy_s_disability/ [Accessed 12 February 2017].

NHS Choices, 2016a. *Muscular dystrophy* [online]. London: NHS Choices. Available from: http://www.nhs.uk/conditions/Muscular-dystrophy/Pages/Introduction.aspx [Accessed 12 December 2016].

NHS Choices, 2016b. *Polio* [online]. London: NHS Choices. Available from: http://www.nhs.uk/Conditions/polio/Pages/Introduction.aspx [Accessed 14 November 2016].

NHS Choices, 2017. *Motor Neurone Disease* [online]. London: NHS Choices. Available from: http://www.nhs.uk/Conditions/Motor-neurone-disease/Pages/Introduction.aspx Accessed 14 November 2016].

Nielsen, J., 1995. *10 Usability Heuristics for User Interface Design* [online]. Fremont, CA: Nielsen Norman Group. Available from: https://www.nngroup.com/articles/ten-usability-heuristics/ [Accessed 10 January 2017].

Norman, D.A. 2002. *The Design of Everyday Things*. 2002 edition. New York, NY: Basic Books.

Norman, D.A. and Draper S.W., 1986. *User Centered System Design: New Perspectives on Human-Computer Interaction*. 1st edition. Hillsdale, NJ: Lawrence Eribaum Associates.

Ontario Adult Autism, 2016. *Quality of Life indicators* [online]. Ontario: Ontario Adult Autism. Available from: http://www.ont-autism.uoguelph.ca/STRATEGIES4.shtml [Accessed 17 November 2016].

Origin Instruments Corporation, 2017. *Sip/Puff Switch* [online]. Grand Prairie, TX: Origin Instruments Corporation. Available from: http://www.orin.com/access/sip_puff/ [Accessed 10 February 2017].

Ortega, G., Wolff, A., Baumgaertner, M. and Kendoff, D., 2008. Usefulness of a head mounted monitor device for viewing intraoperative fluoroscopy during orthopaedic procedures. *Archive Orthopaedic Trauma Surgery.* 128, 1123–1126.

Osteogenesis Imperfecta Foundation, 2016. *Facts about Osteogenesis Imperfecta* [online]. Gaithersburg, MD: Osteogenesis Imperfecta Foundation. Available from:

http://www.oif.org/site/PageServer?pagename=AOI_Facts [Accessed 12 December 2016].

Oviatt, S., 2003. Multimodal interfaces. In: Oviatt, S., ed. *The human-computer interaction handbook*. Hillsdale, NJ: Lawrence Erlbaum Associates Inc., pp. 286-304.

Oxford Living Dictionaries, 2016a. *Philosophy* [online]. Oxford: Oxford University Press. Available from: https://en.oxforddictionaries.com/definition/philosophy [Accessed 29 December 2016].

Oxford Living Dictionaries, 2016b. *Simulation* [online]. Oxford: Oxford University Press. Available from: https://en.oxforddictionaries.com/definition/simulation [Accessed 31 December 2016].

Panasonic UK & Ireland 2017. *Home Monitoring & Control Kit* [online]. Bracknell: Panasonic UK & Ireland. Available from: http://www.panasonic.com/uk/consumer/smart-home/kx-hn6012ew.html [Accessed 28 February 2017].

Papadopoulou, E., Gallacher, S., Taylor, N.K, Howard Williams, M., Blackmun, F.R, Ibrahim, I.S., Lim, M.Y., Mimtsoudis, I., Skillen, P. and Whyte, S., 2014 Combining Pervasive Computing With Social Networking for a Student Environment. *The 12th Australasian Symposium on Parallel and Distributed Computing*, Auckland, 20-23 January 2014. 11-19. ACM Press, New York, NY, USA.

Park, J., Morris, K., Stannard, C. and Hamilton, W., 2014. Design for Many, Design for Me: Universal Design for Apparel Products. *The Design Journal*. 17 (24), 267-290.

Parkinson's UK, 2016. *What is Parkinson's?* [online]. London: Parkinson's UK. Available from: http://www.parkinsons.org.uk/content/what-parkinsons [Accessed 12 December 2016].

Paulk, M.C, Curtis, B., Chrissis, M.B and Weber, C.V., 1993. Capability maturity model, version 1.1. *IEEE Software*. 10 (4), 18-27.

Paulk, M.C, Curtis, B., Chrissis, M.B and Weber, C.V., 1993. Capability maturity model, version 1.1. *IEEE Software*. 10 (4), 18-27.

Pfleging, B., Schneegass, S. and Schmidt., 2012. Multimodal Interaction in the Car - Combining Speech and Gestures on the Steering Wheel. *The 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Portsmouth, NH, USA, 17-19 October 2012. 463-468. ACM Press, New York, NY, USA.

Pham, H.T., Pathirana, P.N. and Caelli, T., 2014. Functional Range of Movement of the Hand: Declination Angles to Reachable Space. *The 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Chicago, USA, 26-30 August 2014. 6230-6233. IEEE Press, New York, NY, USA.

Platz, J. and Clothier, K. 2015. *Motion-controlled Servos with Leap Motion & Raspberry Pi* [online]. San Francisco, CA: PubNub. Available from: https://www.pubnub.com/blog/2015-08-19-

motion-controlled-servos-with-leap-motion-raspberry-pi/ [Accessed 10 February 2017].

Postolache, O., Madeira, R.N., Correia, N. and Girão, P.S., 2009. UbiSmartWheel: a ubiquitous system with unobtrusive services embedded on a wheelchair. *The 2nd International Conference on PErvasive Technologies Related to Assistive Environments,* Corfu, Greece, 9-13 June 2009. 13. ACM Press, New York, NY, USA.

Poulter, S., 2014. *No more flicking switches! Samsung designs smartphone app to turn off lights and home appliances* [online]. London: MailOnline. Available from: http://www.dailymail.co.uk/sciencetech/article-2534751/No-flicking-switches-Samsung-designs-smartphone-app-turn-lights-home-appliances.html [Accessed 12 February 2017].

Powell, R.A., Single, H.M., Lloyd, K.R., 1996. Focus groups in mental health research: enhancing the validity of user and provider questionnaires. *International Journal of Social Psychology*. 42 (3), 193-206.

Prabitha, D.K., Murthy, C. and Kurian, M.Z., 2012. Speech Recognizing Powered Wheelchair for Disabled. *International Conference on Electrical Engineering and Computer Science*, Goa, India, 28 August 2009. 44-48. Institute for Research and Development India, Odisha, India.

Preece, J., Sharp, H. and Roges, Y., 2015. *Interaction Design: Beyond Human-Computer Interaction*. Chichester: John Wiley & Sons.

Pretorian Technologies, 2014. *iOS7 Switch Control Point Mode* [video, online]. YouTube. Available from: https https://www.youtube.com/watch?v=ykvY4lMDytU [Accessed 5 December 2016].

Profita, H.P., Clawson, J., Gilliland, S., Zeagler, C., Starner, T., Budd, J. and Yi-Luen, E., 2013 Don't mind me touching my wrist: a case study of interacting with on-body technology in public. *The 2013 International Symposium on Wearable Computers*, Zurich, 8-12 September 2013. 89-96. ACM Press, New York, NY, USA.

Project Management Solutions, 2011. *Strategies for Project Recovery: A PM Solutions Research Report* [online]. Glen Mills, PA: Project Management Solutions. Available from: http://www.pmsolutions.com/collateral/research/Strategies%20for%20Project%20Recovery%202011.pdf [Accessed 12 February 2017].

Prysm Ndex Ltd., 2017. *Naidex* [online]. Bristol: Prysm Ndex Ltd. Available from: http://www.naidex.co.uk/ [Accessed 28 February 2017].

Rear View Safety Inc., 2017a. *WiFi Backup Camera System* [online]. Brooklyn, NY: Rear View Safety Inc. Available from: https://www.rearviewsafety.co.uk/safety-solutions/backup-camera-systems/wireless-backup-camera-systems/wifi-backup-camera-system.html [Accessed 7 April 2017].

Rear View Safety Inc., 2017b. *Rear View Safety Debuts GoVue, the First Back Up Camera Smartphone App* [online]. Brooklyn, NY: Rear View Safety Inc. Available from: http://www.rearviewsafety.com/safety/rear-view-safety-debuts-govue-the-first-back-up-camera-smartphone-app/ [Accessed 7 April 2017].

Rechtin, E, 2000. Systems *Architecting of Organizations: Why Eagles Can't Swim*. Boca Raton, FL: CRC Press.

Recon Instruments, 2016a. *Recon Jet* [online]. Vancouver: Recon Instruments. Available from: http://www.reconinstruments.com/products/jet/ [Accessed 12 December 2016].

Recon Instruments, 2016b. *Introducing Recon Snow2* [online]. Vancouver: Recon Instruments. Available from: http://www.reconinstruments.com/products/snow2/ [Accessed 12 December 2016].

Reeves, L. M., Lai, J., Larson, J. A. Oviatt, S., Balaji, T. S., Buisine, S., Collings, Cohen, P., Kraal, B., Martin, J. C., McTear, M., Raman, T., K. Stanney, K. M., Su, H. and Q. Y. Wang, Q. Y., 2004. Guidelines for multimodal user interface design. *Communications of the ACM - Multimodal interfaces that flex, adapt, and persist*. 47 (1), 57-59.

Richards, R.R., An, K.N., Bigliani, L.U., Friedman, R.L., Gartsman, G.M. and Gristina, A.G., 1994. A standardized method for the assessment of shoulder function. *Journal of Shoulder & Elbow Surger*y. 3, 349-352.

Robertson, J. and Robertson, S., 2004. *VolereVolèreVolere Requirements Specification Template Edition 10.1*. London: The Atlantic Systems Guild Ltd. Available from: http://www.inf.ed.ac.uk/teaching/courses/seoc/2007_2008/resources/volere-template.pdf [Accessed 8 May 2015].

Robertson, J. and Robertson, S., 2009. *A tomic Requirements: where the rubber hits the road.* London: The Atlantic Systems Guild Ltd. Available from: http://www.volere.co.uk/pdf%20files/06%20Atomic%20Requirements.pdf [Accessed 30 December 2016].

Rose, D., 2004. *Don't call me handicapped!* [online]. London: BBC News. Available from: http://news.bbc.co.uk/1/hi/magazine/3708576.stm [Accessed 28 February 2017].

Royal Literary Fund, 2016. *What is a literature review?* [online]. London: Royal Literary Fund. Available from: http://www.victoria.poole.sch.uk/ [Accessed 21 December 2016].

Saha, D. and Mukherjee, A., 2003. Pervasive computing: a paradigm for the 21st Century. *Computer*. 36, 25-31.

Salmon, P., Stanton, N., Baber, C., Walker, G. and Green, D., 2004. *Human Factors Design and Evaluation Methods Review* [online]. Yeovil: Defence Human Capability Science & Technology Centre. Available from: https://www.defencehumancapability.com/Portals/0/HFIDTC/HFI%20Methods%20and%20Models/Phase%201/hf-design-evaluation-methods.pdf [Accessed 10 January 2016].

Saunders, M.N.K., Lewis, P. and Thornhill, A., 2015. *Research Methods for Business Students*. 7th edition. Harlow: Pearson Education.

Scapens, R. W., 1990. Researching management accounting practice: the role of case study methods. *British Accounting Review.* 22, 259-281.

Schalk, G. and Leuthardt, E.C., 2011. Brain-Computer Interfaces Using Electrocorticographic Signals. *IEEE Reviews in Biomedical Engineering*. 4 (1), 140-154.

Schmidt, A., Spiekermann, S., Gershman, A. and Michahelles, F., 2006. Real-World Challenges of Pervasive Computing. *Pervasive Computing*. 5 (3), 91-93.

Scientific Working Group on Friction Ridge Analysis, Study and Technology (SWGFAST), 2001. *Validation of Research and Technology* [online]. SWGFAST. Available from: http://www.swgfast.org/documents/validation/010808_Validation_1.0.pdf [Accessed 6 January 2017].

SEBoK, 2016a. *Systems of Systems (SoS)* [online]. SEBoK. Available from: http://sebokwiki.org/wiki/Systems_of_Systems_(SoS) [Accessed 17 November 2016].

SEBoK, 2016b. *System Architecting Approaches for Systems of Systems* [online]. SEBoK. Available from: http://sebokwiki.org/wiki/Architecting_Approaches_for_Systems_of_Systems [Accessed 12 February 2017].

Sharp, H., Taylor, J., Evans D. and Hayley, D., 2015. *Establishing Requirements for a mobile learning system.* Chichester: John Wiley & Sons. Available from: http://www.id-book.com/casestudy_10-2_2.php [Accessed 30 December 2016].

Shine, 2016. *Types of spina bifida* [online]. Peterborourgh: Shine. Available from: http://www.shinecharity.org.uk/spinabifida/more-about-spina-bifida/types-of-spina-bifida [Accessed 12 December 2016].

Shneiderman, B. and Plaisant, C., 2014. *Designing the User Interface.* 5th edition. Harlow: Pearson Education.

Simpson, R., LoPresti, E., Hayashi, S.,Nourbakhsh, I. and Miller, D., 2006. The Smart Wheelchair Component System. *Journal of Rehabilitation Research & Development*. 41 (3B), 429-442.

Snider, H. and Takeda, N., 2008. *Design for All: implications for bank operations* [online]. Washington, WA: The World Bank. Available from: http://siteresources.worldbank.org/DISABILITY/Resources/Universal_Design.pdf [Accessed 12 February 2017].

Sommerville, I., 2015. *Software Engineering*. Tenth edition. Harlow: Pearson Education.

Sörös, G., Daiber, F. and Weller, T., 2013. Cyclo: a personal bike coach through the glass. *The SIGGRAPH Asia 2013 Symposium on Mobile Graphics and Interactive Applications*, Hong Kong, Hong Kong, 19-23 November 2013. ACM Press, New York, NY, USA.

Spence, I. and Bittner, K., 2005. *What is iterative development?* [online]. New York, NY: IBM developerWorks. Available from: http://www.ibm.com/developerworks/rational/library/may05/bittner-spence/ [Accessed 28 February 2017].

Srivastava, P., Chatterjee, S. and Thakur, R., 2014. Design and Development of Dual Control System Applied to Smart Wheelchair using Voice and Gesture Control. *International Journal of Research in Electrical & Electronics Engineering*, 2 (2), 1-9.

Stanford, V., 2002. Using pervasive computing to deliver elder care. P*ervasive Computing*. 1 (1), 10-13.

Stanton, N.A., Salmon, P.M., Walker, G.H., Baber, C. and Jenkins, D.P., 2013. *Human Factors Methods: A Practical Guide for Engineering and Design*. 2nd edition. Farnham: Ashgate Publishing.

Stern Law Group PLLC., 2016a. *Classification based on severity level* [online]. Novi, MI: Stern Law Group PLLC. Available from:

http://cerebralpalsy.org/about-cerebral-palsy/definition/ [Accessed 12 December 2016].

Stern Law Group PLLC., 2016b. *Definition of cerebral palsy* [online]. Novi, MI: Stern Law Group PLLC. Available from: http://cerebralpalsy.org/about-cerebral-palsy/types-and-forms/ [Accessed 12 December 2016].

Stewart, D.W. and Shamdasani, P.N., 2014 *Focus groups: theory and practice*. 20th edition. London: Sage Publications.

Stoneburner, G., Goguen, A.Y. and Feringa, A., 2002. *Sp 800-30. Risk management guide for information technology systems.*

Stroke Association, 2015. *What is a stroke?* [online]. London: Stroke Association. Available from: https://www.stroke.org.uk/what-stroke/what-stroke [Accessed 12 February 2017].

Teixeira, A., Häamäaläainen, A., Avelar, J, Almeida, N, Néemeth, G., Fegyo, T., Zainkóo, C., Csapóo, T., Tóoth, B., Oliveira, A. and Sales Dias, M. 2014. Speech-centric Multimodal Interaction for Easy-to-access Online Services – A Personal Life Assistant for the Elderly. *Procedia Computer Science.* 27, 389-397.

The Brittle Bone Society, 2016. *About OI* [online]. Dundee: The Brittle Bone Society. Available from: http://www.brittlebone.org/about-oi/about-oi/ [Accessed 12 December 2016].

The VR Shop, 2015. *MicroOptical MV-1* [online]. The VR Shop. Available from: https://www.virtual-reality-shop.co.uk/microoptical-mv-1/ [Accessed 12 January 2017].

Thuret, S., Moon, L.D.F. and Gage, F.H. 2006. Therapeutic interventions after spinal cord injury. *Nature Reviews Neuroscience*. 7 (1), 628-643.

TLD Vision s.r.o., 2015. *TLD 2.0* [online]. Zelec: TLD Vision s.r.o. Available from: http://www.tldvision.com/product_tld2.php [Accessed 12 February 2017].

Toluna, 2015. *Create Free Online Surveys & Questionnaire*s [online]. London: Toluna. Available from: https://www.quicksurveys.com/ [Accessed 12 February 2017].

Turk, M., 2013. Multimodal interaction: A review. *Pattern Recognition Letters*. 36, 189-195.

Tüzün, H., Telli, E. and Alir, A., 2016. Usability testing of a 3D touch screen kiosk system for way-finding. *Computers in Human Behavior*, 61, 73-79.

Ubeda, V., Ianez, E. and J.M. Azor, 2011. Wireless and Portable EOG Based Interface for Assisting Disabled People. *IEEE Transactions on Mechatronics*. 16 (5), 870-873.

Union of the Physically Impaired Against Segregation, 1976. *Fundamental Principles of Disability*. London: Union of the Physically Impaired Against Segregation.

Usability Body of Knowledge (Usability BoK), 2010a. *Cognative Walkthrough* [online]. User Experience Professionals Association. Available from: http://www.usabilitybok.org/cognitive-walkthrough [Accessed 6 January 2017].

Usability Body of Knowledge (Usability BoK), 2010b. *Think Aloud Testing* [online]. User Experience Professionals Association. Available from: http://www.usabilitybok.org/think-aloud-testing [Accessed 10 January 2017].

Usability.gov, 2016. *Usability Evaluation Basics* [online]. Washington, WA: U.S. Department of Health & Human Services. Available from:

https://www.usability.gov/what-and-why/usability-evaluation.html [Accessed 17 November 2016].

Usability.gov, 2017. *Focus Groups* [online]. Washington, WA: U.S. Department of Health & Human Services. Available from: https://www.usability.gov/how-to-and-tools/methods/focus-groups.html [Accessed 6 January 2017].

van Berlo, A., 2002. Smart home technology: Have older people paved the way? *International Journal on the fundamental aspects of technology to serve an aging society*. 2 (1), 77-87.

Vasen, A.P., Lacey, S.H., Keith, M.W., Shaffer, J.W. and Cleveland, O.H., 1995 Functional range of motion of the elbow. *Journal of Hand Surgery*. 20, 288-292.

Vercelli, A. and Boido, M., 2015. Spinal Cord Injury. In: Zigmond, M.J., Coyle, J.T. and Rowland, L.P., eds. 2015. *Neurobiology of Brain Disorders: Biological Basis of Neurological and Psychiatric Disorders*. London: Elsevier, 207-218.

Virtual Aviation, 2016. *Virtual Aviation Flight Training* [online]. Cambridge: Virtual Aviation. Available from: http://www.virtualaviation.co.uk/[Accessed 31 December 2016].

Washington State Department of Social and Health Services, 2014. *Range of Joint Motion Evaluation Chart* [online]. Olympia, WA: Washington State Department of Social and Health Services. Available from: https://www.dshs.wa.gov/sites/default/files/FSA/forms/pdf/13-585a.pdf [Accessed 21 December 2016].

Weiser, M., 1991. The Computer for the 21st Century. *Scientific American*. 265 (3), 66-75.

Williams-Zahir, J., 2015. *Older Adults Should Not Be Left Behind: Its Your Time*. USA: Jennell Williams-Zahir.

Woolf, N., 2015. G*oogle Glass ceases production 'in present form'* [online]. London: The Guardian. Available from: https://www.theguardian.com/technology/2015/jan/15/google-glass-ceases-production-for-now [Accessed 12 December 2016].

Work Package 2, Deliverable D2.1. Loughborough: Loughborough University. Report TAREA-PU-WP2-R-LU-9.

World Health Organization, 1980. *International Classification of Impairments, Disabilities and Handicaps: A manual of classification relating to the consequences of diseases, published in accordance with resolution WHA 29.35 of the 29th World Health Assembly*. Geneva: World Health Organization.

World Health Organization, 2001a. *International Classification of Functioning, Disability and Health: Short Version: ICF*. Geneva: World Health Organization.

World Health Organization, 2001b. *ICF Checklis*t. Geneva: World Health Organization.

World Health Organization, 2007. International Classification of Functioning, Disability and Health: Children & Youth Version: ICF. Geneva: World Health Organization.

World Health Organization, 2011. *World Report on Disability*. Geneva, Switzerland: World Health Organization.

Wu, T., Dameff, C. and Tully, J., 2014. Integrating Google GLASS into simulation-based training: experincesexperiences and future directions. *Journal of Biomedical Graphics and Computing*. 4, 49–54.

Xsens, 2015. *MTw Development Kit* [online]. An Enschede: Xsens. Available from: https://www.xsens.com/products/mtw-development-kit/ [Accessed 12 February 2017].

Ye, J., Dobson, S. and McKeever, S., 2011. Situation identification techniques in pervasive computing: A review. *Pervasive and Mobile Computing*. 8 (1), 36-66.

Zawati, O.A.L. and Dweiri, F., 2016. Application of Quality Function Deployment to improve smart services applications, Dubai public entity as a case study. *The IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, 4-7 December 2016. IEEE Press, New York, NY, USA.

Appendices

Appendix A: Input Devices

Table 20: Available input devices

Chin Joystick:	
Golf Ball Joystick:	
Standard Joystick:	
Mushroom Joystick:	
T-bar Joystick:	

Switch:	

Appendix B: Organisations Contacted

Table 21: Contacted organisations

Organisation	Outcome	Response
Access Dorset	Phoned Contact DOTS below	1 survey received from DOTS
Bobath Centre¸ London	Author went to Bobath as a child Emailed with description and Phoned leaving left voice message	Sent further email with survey questions, flier and Motability article attached on 28/05/14 Posted paper copies 2/6/14
Diverse Abilities Plus, Poole	Phoned and emailed	1 survey received, interested in future trials
Dorset Wheelchair Services, St. Leonards	Online and paper questionnaires sent	1 survey received
DOTS Disability Community Interest Group, Bournemouth	Emailed and questionnaire completed	1 survey received
Leonard Cheshire Disability, Poole	Emailed and questionnaire completed	3 surveys received
Treloars, Farnham	Have an assistive technology department. Phoned	2 responses to the survey
Victoria Education Centre, Poole	Emailed, phoned and suggested possible dates to interview post-16 students	Visited on 04/06/2014 to conduct 5 interviews Visited on 27/06/2014 to conduct 5 interviews
Weymouth & Portland Access Group	Emailed	1 survey received

Appendix C: Requirements Elicitation Survey

What is your gender?

☐ Male	☐ Female

Which age group do you belong to?

☐ <13	☐ 13-25	☐ 26-40	☐ 41-54	☐ 55+

What is your employment?

What is your disability?

Are you colour blind?

☐ Yes	☐ No

Do you have finger dexterity impairment?

☐ Yes	☐ No

Do you have speech impairment?

☐ Yes	☐ No

Do you live independently?

☐ Yes	☐ No

Are you a permanent user of a powered wheelchair?

☐ Yes	☐ No

What is the make/model of your powered wheelchair?

How do you control your powered wheelchair?

☐ By joystick	☐ By mouth	☐ Other, please specify:

Do you find your powered wheelchair easy to control?

☐ Yes	☐ No

How long have you used a powered wheelchair for?

☐ Less than 1 year	☐ 1-2 years	☐ 3-5 years	☐ More than 5 years

Do you own a smartphone?

☐ Yes	☐ No

What is the make of your smartphone?

How do you control your smartphone (by touch, voice, joystick, etc.)?

Do you have any technologies currently installed in your home to assist with your living (e.g. motorized curtains, automatic doors, etc.)?

Number this list of tasks (around the house), so that the task you experience most difficulty performing is number 1:

- Switching lights on and off
- Opening and closing curtains
- Navigating your powered wheelchair around the house
- Switching appliances on and off
- Opening and closing windows
- Operating an electric bed

Are there any other tasks around the house that you experience difficulty performing from your powered wheelchair and where would the task(s) be placed in the above list?

For the top three tasks (including any 'other' tasks) that you experience most difficulty performing, provide a description of the causes of these difficulties?

Number this list of doors (around the house), so that the door you experience most difficulty opening and closing is number 1:

- Tumble Dryer Door
- Fridge/Freezer Doors
- Cupboard Doors
- Washing Machine Door
- Microwave Door
- Cooker Door
- Garage Doors
- Front, Back and Patio Doors
- Room Doors

Are there any other doors around the house that you experience difficulty opening and closing from your powered wheelchair and where would the door(s) be placed in the previous list?

For the top three doors (including any 'other' doors) that you experience most difficulty opening and closing, provide a description of the causes of these difficulties?

Number this list of appliances, so that the appliance you experience most difficulty operating is number 1:

- TV / DVD Player / PVR / Video Recorder
- Heating Appliances
- Dishwasher
- Washing Machine
- Tumble Dryer

- Cooker
- Microwave
- Kettle
- Sound Systems

Are there any other appliances around the house that you experience difficulty operating from your powered wheelchair and where would the appliance(s) be placed in the above list?

For the top three appliances (including any 'other' appliances) that you experience most difficulty operating, provide a description of the causes of these difficulties?

Number this list of activities (outside the house), so that the activity you experience most difficulty performing is number 1:

- Working in your Workplace / School / College / University
- Going to Restaurants / Cafes
- Visiting Tourist Attractions
- Using Public Transport
- Staying in Overnight Accommodation
- Going Shopping
- Using Lifts
- Operating Vehicle Adaptations

Are there any activities outside the house that you experience difficulty operating from your powered wheelchair and where would the activity(s) be placed in the above list?

For the top three activities outside the house (including any 'other' activities) where you experience the most difficulty, provide a description of the cause of these difficulties?

Number this list of weather conditions, so that the condition you experience most difficulty performing tasks under is number 1:

- Snow
- At Night
- Excessive Heat
- Bright Sunlight
- Rain

For the top three weather conditions that you experience most difficulty performing tasks under, provide a description of the causes of these difficulties?

Do you have an adapted vehicle?

☐ Yes ☐ No

If yes, do you experience difficulty operating any vehicle adaptions?

If you drive, do you experience difficulty operating the vehicle's secondary controls such as indicators or windscreen wipers?

Number this list of technologies, so that the technology you would find the most useful is number 1:

- Digital Pen (transfers handwriting to a smartphone)
- Head Mounted Display (used to select functions by viewing a virtual display)
- Smartphone (used to select functions by touch)
- Smartphone using Eye Tracking (used to select functions by sight)
- Smartphone using Head Tracking (used to select functions by head movements)
- Smartphone using Voice (used to select functions by voice)

For the three technologies that most interest you, provide a description of a task where the technologies would be most helpful:

Do you have any further requirements for a SmartPowerchair?

Thank you for participating. Your contribution and time are greatly appreciated.

Appendix D: Publications

Paper 1: Evaluating the Usability of an Automated Transport and Retrieval System

Full Reference: Whittington, P., Dogan, H. and Phalp, K., 2015a. Evaluating the Usability of an Automated Transport and Retrieval System. The 5th International Conference on Pervasive and Embedded Computing and Communication Systems, Angers, France, 11-13 February 2015. 59-66. Science and Technology Press, Lisbon, Portugal.

Abstract: The Automated Transport and Retrieval System (ATRS) is a technically advanced system that enables a powered wheelchair (powerchair) to autonomously dock onto a platform lift of a vehicle using an automated tailgate and a motorised driver's seat. The proposed prototype, SmartATRS, is an example of pervasive computing that considerably improves the usability of ATRS. Two contributions have been made to ATRS: an improved System Architecture incorporating a relay board with an embedded web server that interfaces with the smartphone and ATRS, and an evaluation of the usability of SmartATRS using the System Usability Scale (SUS) and NASA Task Load Index (NASA TLX). The contributions address weaknesses in the usability of ATRS where small wireless keyfobs are used to control the lift, tailgate and seat. The proposed SmartATRS contains large informative buttons, increased safety features, a choice of interaction methods and easy configuration. This research is the first stage towards a "SmartPowerchair", where pervasive computing technologies would

be integrated into the powerchair to help further improve the lifestyle of disabled users.

Paper 2: SmartPowerchair: to boldly go where a powerchair has not gone before

Full reference:

Whittington, P., Dogan, H. and Phalp, K., 2015b. SmartPowerchair: to boldly go where a powerchair has not gone before. Ergonomics & Human Factors 2015, Daventry, UK, 13-16 April 2015. 233-240. CRC Press, London, UK.

Abstract: A survey was conducted targeting a user community of people in powered wheelchairs (powerchairs) as the requirements elicitation phase of a proposed SmartPowerchair, using online and paper-based methods. Analysis of the survey results using graphs and statistics led to key findings. These showed that opening/closing curtains, windows, doors and operating heating controls were the most difficult tasks to perform from a powerchair and also that an integrated smartphone operated by either touch or head tracking would be the most useful to potential SmartPowerchair users. This research is supported by a usability evaluation case study of a pervasive assistive technology which revealed System Usability Scale (SUS) and NASA Task Load Index (TLX) results.

Paper 3: SmartPowerchair: A Pervasive System of Systems

Full reference:

Whittington, P. and Dogan, H., 2015c. SmartPowerchair: A Pervasive System of Systems. The 10th International Conference on System of System Engineering, San Antonio, TX, USA, 18-20 May 2015. IEEE Press, New York, NY, USA.

Abstract: This paper presents the characterisation of a concept System of Systems called the SmartPowerchair, in which existing pervasive technologies are integrated into a standard powered wheelchair to enhance the quality of life through independent living. Traditional Systems Engineering focuses on building the right system whereas System of Systems focuses on selecting the right combination of systems and their interactions to satisfy a set of frequently changing requirements. The SmartPowerchair can be characterised as a System of Systems due to the integration of a finite number of constituent systems which are independent and interoperable, and networked together for a period of time to achieve a certain higher goal. A high-level two-dimensional System of Systems model is developed to illustrate the lifecycle stages of System of Systems and different levels including the Component, System, System of Systems and Capability levels. Usability evaluations and workload measurements of a constituent system is also provided.

Paper 4: Improving life for people with disabilities

Full reference: Whittington, P. and Dogan, H., 2015d. Improving life for people with disabilities. The Ergonomist, 542, 12-13.

Paper 5: SmartDisability : A smart system of systems approach to disability

Full reference: Whittington, P. and Dogan, H., 2016a. SmartDisability: A smart system of systems approach to disability. The 11th International Conference on System of System Engineering, Kongsberg 12-16 June 2016. New York, NY: IEEE Press.

Abstract: This paper introduces the SmartDisability Framework; a System of Systems to consider mappings between the Disability Types, Range of Movement and Interaction Mediums to produce Technology and Task recommendations. Each element is seen as a constituent system that relies on interaction between the user and technology. The recommended technologies are viewed as independent and operable constituent systems that are networked together to assist people with disability. The SmartDisability conceptual model (based on the familiar disability symbol) and extracts from the initial development stage of the framework are presented. The framework has been populated through a systematic literature review of disability classification, Range of Movement, interaction mediums, 'off-the-shelf' technologies and tasks. The framework was augmented by the results of a previously conducted requirements elicitation process, involving surveys and semi-structured interviews, and a user evaluation with head tracking technology. Quality Function Deployment determined the relationships within the framework to ensure that user requirements were fully analysed. The anticipated validation process involving a focus group utilising fictional personas and routes to exploitation (through the development of an application) are also discussed.

Paper 6: Improving user interaction through a SmartDisability Framework

Full reference: Whittington, P. and Dogan, H., 2016b. Improving user interaction through a SmartDisability Framework. British HCI 2016 Conference, Bournemouth 11-15 July 2016.

Abstract: This paper introduces the SmartDisability Framework to consider mappings between disability type, Range of Movement and interaction mediums to produce technology and task recommendations to enhance user interaction. The SmartDisability conceptual model (based on the familiar disability symbol) and extracts from the initial development stage of the Framework are presented. The Framework has been populated through the knowledge obtained from state-of-the-art literature reviews of disability classification, Range of Movement, interaction mediums, 'off-the-shelf' technologies and tasks. The Framework was augmented by requirements elicitation results and a described usability evaluation involving a simulation of the SmartATRS smartphone system to control the Automated Transport and Retrieval System (ATRS). ATRS is a technically-advanced system that enables a powered wheelchair (powerchair) to autonomously dock onto a platform lift of a vehicle using an automated tailgate and a motorised driver's seat. The usability of touch and head-based interaction methods were measured using System Usability Scale (SUS) and NASA Task Load Index (NASA TLX) and demonstrated that fingers were more usable interaction method, as head tracking required a full range of neck movement. This SmartDisability Framework is anticipated to be validated through focus groups

utilising fictional personas that involve experts from the domains of healthcare, computing and occupational therapy. The framework will be routed to exploitation through the development of a smartphone or web-based application.

Paper 7: A SmartDisability Framework: enhancing user interaction

Full reference: Whittington, P. and Dogan, H., 2016c. A SmartDisability Framework: enhancing user interaction. British HCI 2016 Conference, Bournemouth 11-15 July 2016.

Abstract: This paper aims to improve user interaction by establishing a SmartDisability Framework for the healthcare and assistive technology industries through considering mappings between Disability Types, Range of Movement (ROM) and Interaction Mediums to produce Technology and Task recommendations. The SmartDisability conceptual model (based on the familiar disability symbol) is the result of the Framework being populated through a systematic literature review of disability classification, ROM, interaction mediums, 'off-the-shelf' technologies and tasks. A previously conducted requirements elicitation process, involving surveys and semi-structured interviews, and a described usability evaluation involving touch and head-based interaction methods augmented the framework. The evaluation was conducted using a simulation of SmartATRS; a smartphone system that controls Automated Transport and Retrieval System (ATRS) enabling a user with disability to autonomously dock a powered wheelchair (powerchair) onto a platform lift of a vehicle, as well as controlling an automated tailgate and a motorised driver's seat. System Usability

Scale (SUS) and NASA Task Load Index (NASA TLX) was applied to measure the usability of each interaction method. Discussions of future work are provided including the anticipated framework validation process that will utilise focus groups considering fictional personas. The SmartDisability Framework will be exploited through the development of a smartphone or web-based application.

Paper 8: SmartPowerchair: Characterisation and Usability of a Pervasive System of Systems

Full reference: Whittington, P. and Dogan, H., 2016d. SmartPowerchair: Characterisation and Usability of a Pervasive System of Systems. IEEE Transactions on Human Machine Systems.

Abstract: A characterization of a pervasive system of systems (SoS) called the SmartPowerchair is presented, integrating pervasive technologies into a standard powered wheelchair (powerchair). The SmartPowerchair can be characterized as a The SmartPowerchair can be characterized as a SoS due to focusing on selection of the correct combination of independent and interoperable systems that are networked for a period of time to achieve the specific overall goal of enhancing the quality of life for people with disability. A high-level 2-D SoS model for the SmartPowerchair is developed to illustrate the different SoS lifecycle stages and levels. The results from a requirements elicitation study consisting of a survey targeting powerchair users were the input to a hierarchical task analysis defining the supported tasks of the SmartPowerchair. The system architecture of one constituent system (SmartATRS) is described as well as the results of a usability evaluation containing workload measurements. The establishment of the SmartAbility framework

was the outcome of the evaluation results that concluded range of movement (ROM) was the determinant of suitable technologies for people with disability. The framework illustrates how a SoS approach can be applied to disability to recommend interaction mediums, technologies, and tasks depending on the disability, impairments, and ROM of the user. The approach, therefore, creates a "recommender system" by viewing disability type, impairments, ROM, interaction medium, technologies, and tasks as constituent systems that interact together in a SoS.

Paper 9: From Requirements to Operation: Components for Risk Assessment in a Pervasive System of Systems

Full reference: Ki-Aries, D., Dogan, H., Faily, S., Whittington, P. and Williams,C., 2017. From Requirements to Operation: Components for Risk Assessment in a Pervasive System of Systems. The 4th International Workshop on Evolving Security and Privacy Requirements Engineering, Lisbon, Portugal 4 September 2017.

Abstract: Framing Internet of Things (IoT) applications as a System of Systems (SoS) can help us make sense of complexity associated with interoperability and emergence. However, assessing the risk of SoS is a challenge due to the independence of component systems, and their differing degrees of control and emergence. This paper presents three components for SoS risk assessment that integrate with existing risk assessment approaches: Human System Integration (HSI), Interoperability identification and analysis, and Emergent behaviour evaluation and control measures. We demonstrate the

application of thesecomponents by assessing a pervasive SoS: a SmartPowerchair.

Appendix E: Requirements Elicitation Survey Transcripts

Table 22: Transcription data (1)

Participant	Technologies installed in home	Other home tasks causing difficulties	Description of difficulties with home tasks	Other doors causing difficulties
P01	Possum environmental control in the bedroom	No other home tasks	Opening / closing windows will be impossible for me because they require manual dexterity that I don't have. Likewise with curtains. Likewise with electric bed	No other doors
P02	None	No other home tasks	As I am in my wheelchair, I find it difficult to reach across my dressing table to open the windows or open the curtains.	No other doors
P03	Lift and hand activated doors	No other home tasks	Only windows are a problem as they are too stiff	No other doors
P04	None	No other home tasks	No description given	No other doors
P05	None	No other home tasks	I am unable to perform manual tasks	No other doors
P06	None	Reaching anything from shelves	I cannot reach the windows, appliances or curtains	No other doors

Participant	Technologies installed in home	Other home tasks causing difficulties	Description of difficulties with home tasks	Other doors causing difficulties
P07	None	No other home tasks	Having to stretch and reach causes big problems. Depending on where the switch is on the appliances makes some easier than others. Pulling curtains is also difficult	No other doors
P08	Lift, Electric bed	No other home tasks	No description given	No other doors
P09	Electric bed	No other home tasks	Hard to get chair around furniture. Can't bend down easily to appliances. Windows - can't get up on sofa to open.	No other doors
P10	Bed hoist, plinth to assist with bathing (can be controlled by respondent)	No other home tasks	Opening and closing curtains difficult because of stuff in the way.	No other doors
P11	None	No other home tasks	When navigating around the house I collide with doors. I don't operate curtains, appliances or windows.	No other doors
P12	Electric bed	No other home tasks	Opening and closing curtains and switching lights on and off are the most difficult. I can't reach windows.	No other doors

Participant	Technologies installed in home	Other home tasks causing difficulties	Description of difficulties with home tasks	Other doors causing difficulties
P13	None	Any tasks involving arm extensions	Cannot extend arms to reach windows, curtains and lights.	No other doors
P14	Wheelchair hoist	No other home tasks	Navigating powerchair around the house is difficult because the house is small and the doors are not wide enough.	No other doors
P15	Chin joystick to control computer	No other home tasks	Switching lights on and off, opening and closing curtains opening and closing windows are the most difficult from the powerchair.	No other doors
P16	Nursing bed	No other home tasks	Opening and closing windows and switching on appliances are most difficult as I cannot reach very well. Lights with pull cords are easier.	No other doors
P17	Automatic door	No other home tasks	Opening and closing curtain and windows are difficult as they are not at the right height. Navigating the furniture around the house is the next most difficult as there is too much obstruction from furniture	No other doors

Table 23: Transcription data (2)

Participant	Description of difficulties with doors	Other appliances causing difficulties	Description of difficulties with operating appliances	Other outdoor tasks causing difficulties
P01	Out of reach and insufficient manual dexterity	No other appliances	My cooker is an Aga with very heavy doors which are dangerous and too heavy for me to operate.	Travelling by air and train
2	As I am in my wheelchair, I find it difficult to reach doors.	No other appliances	As I have no feelings from the chest down, I cannot sense heat so I have to be very careful when operating anything hot or even warm as I cannot feel it.	I find using lifts can be difficult as some lifts, the doors are not wide enough for my chair or the buttons are to too high to reach. The same happens when you are out in supermarkets, things you require might be out of reach when you are in your wheelchair.
P03	No difficulties	No other appliances	No difficulties	No other tasks
P04	No difficulties	No other appliances	No difficulties	No other tasks
P05	No description given	No other appliances	No difficulties	No other tasks

Participant	Description of difficulties with doors	Other appliances causing difficulties	Description of difficulties with operating appliances	Other outdoor tasks causing difficulties
P06	I am unable to reach the door handles to open the doors.	No other appliances	I am unable to reach appliances	Using some disabled toilets - as they are too small.
P07	The front door means I have to stand and pull the door towards me. The garage door is very heavy. Washing machine door does not allow me to get close enough to the machine	No other appliances	The kettle is too heavy for me to lift so it is dangerous. Heating appliances have very small switches. Microwave - I don't have the strength to lift things in & out.	No other tasks
P08	No description given	No other appliances	No description given	No other tasks
P09	Can't get out of powerchair	No other appliances	Because I can't get out of powerchair, getting new chair that stands up so that I can reach cupboard and open it.	In the garden
P10	No description given	No other appliances	I only use TV which is easy. I use the cooker with help.	No other tasks

Participant	Description of difficulties with doors	Other appliances causing difficulties	Description of difficulties with operating appliances	Other outdoor tasks causing difficulties
P11	Front, back and patio doors are difficult to unlock	iPad and computer	I only use TV which is easy.	Using a manual wheelchair
P12	Front, back, patio and garage doors have keys that I cannot reach. I can't open room doors.	No other appliances	I use the TV with the remote control which is easy.	No other tasks
P13	Difficulty with arms	No other appliances	Kettle, heating appliances and microwave are the most difficult due to heat.	Using some public toilets are difficult
P14	Garage doors and front, back and patio doors are difficult.	PlayStation	Heating appliances are difficult to operate	No other tasks
P15	Front, back and patio doors are the most difficult as both handles need to be turned.	No other appliances	Kettle is the most difficult as lifting or pressing is hard.	No other tasks

Participant	Description of difficulties with doors	Other appliances causing difficulties	Description of difficulties with operating appliances	Other outdoor tasks causing difficulties
P16	Unable to reach cupboard doors. Cooker / microwave doors are difficult because they are hot.	No other appliances	Heating appliances and cooker are most difficult. Ensuring that the timer is right on heating appliances is difficult.	No other tasks
P17	Garage door is the only difficult door as I couldn't lift it.	No other appliances	Heating appliances are the most difficult due to dials. The cooker and microwave are the next most difficult.	No other tasks

Table 24: Transcription data (3)

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P01	Wheelchair accessibility	Due to the disruption to my autonomic nervous system as a result of acquiring a spinal cord injury, my body is unable to tolerate extremes of hot and cold.	I don't operate the adapted vehicle. I'm simply secured in my wheelchair into the back of the vehicle and someone else drives it.	Operated by carer
P02	Things are out of reach	I find that if it is cold or wet, it effects my conditions and causes me excessive pain	No	Not applicable
P03	Outdoor lifts can have buttons that are out of reach. Some outdoor tasks can require a carer to be present	Snow is difficult.	No	Not applicable
P04	No description given	No description given	No	Not applicable
P05	No description given	No description given	No	Not applicable

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P06	Finding accommodation that is suitable is very difficult. Sometimes lifts are very narrow	Rain- short circuits powerchair. Snow- too slippery freezes the frame of powerchair. Bright sunlight- cannot see properly.	Yes	No response given
P07	Haven't got a car but about to be assessed. I still need a hospital bed. I don't have the confidence to use public transport on my own.	Bright sunlight means I can't see clearly and I worry other vehicles won't see me. At night really is confidence that I will be seen. My powerchair slips and loses control in snow.	No	Not applicable
P08	No description given	No description given	Yes	Operated by parents

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P09	Parents have to move stuff in the garden so I can move around. Visiting tourist attractions difficult. Trains are accessible. Using lifts is easy.	Excessive heat is too hot. Don't go out at night or in rain.	No	Not applicable
P10	Public transport is not accessible	Snow is difficult as powerchair becomes stuck.	Yes	Operated by parents
P11	Only uses a manual wheelchair outside and therefore has to be pushed by a carer	Does not use a powerchair outside of buildings	No	Not applicable

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P12	Trains are difficult because of the gap. Going shopping and using lifts are easy.	Snow is the most difficult. In heat and in sunlight sun gets in my eyes and I can't see to drive. In the shade I can't see what is in front of me. I use a rain cover.	Yes	Operated by parents
P13	Public toilets can be too small for a powerchair	Snow is most difficult due to the cold and rain and sunlight is difficult due to not being able to see.	Yes	Operated by my carer. I'm not able to drive myself

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P14	Visiting tourist attractions is the most difficult as rides are not accessible. Using lifts can be difficult if they are small, buses are not always accessible, and pushchairs are in the way.	Snow and rain are most difficult conditions as the powerchair slips and slides. At night is the next most difficult due to not having lights.	No	Not applicable
P15	No difficulties	Snow is the only difficult condition	No	Not applicable

Participant	Description of difficulties with outdoor tasks	Challenging weather conditions	Owns an adapted vehicle	Operator of the adapted vehicle
P16	Using buses can be difficult if bus is not adapted for powerchair. Staying in overnight accommodation and visiting tourist attractions are the next most difficult if they are not accessible.	Snow is the most difficult. At night is difficult as eyesight is not good enough to see kerbs. Bright sunlight is blinding.	Yes	Operated by parents
P17	Going to restaurants is the most difficult tasks due to ordering from a menu.	Snow is the most difficult as the powerchair gets stuck. Rain and bright sunlight are also challenging.	Yes	Operated by parents

Appendix F: Dynamic Controls Requirements Specification

Industrial Requirements

Dynamic Controls

Disability Type

Single solution to fit multiple needs - Each end user has a different needs how do we get a single solution that can meet the wide range of disability needs. Reference Rachael's work? Could a simplified model be built to address this? May show multiple modes of operation based on condition.

Cognitive Challenge - A lot of end users have not had previous access to ICT, how do we provide them with a solution that allows them to gain confidence with ICT, without being overwhelmed. How can a user interface start off simple and develop with their experience. Consider computer games where you have different levels.

Motor Challenge – With the introduction of new technology it will involve new unfamiliar movements consider the speed of a cursor. Level one is programmable speeds; adjusted by an intervention by the end user / therapist. Level two is to automate this, can we automatically identify when someone's skills have improved.

Environment

To have the environment adapted is expensive and may not be funded. What can be done to optimise the cost / feature balance?

Option 1: If you can get it fully funded what current home automation technologies are most encompassing of end user needs?

Option 2: Are there ways to have an expandable solution, which can sit on a common platform (industry standard) and an end user can build up over time?

How do we maintain access between an end user and their technology interface when they are not in their power chair e.g. when in bed, driving a car, in hospital?

Technology

What are the options to bridge between a power chair and these systems (this is almost a history of the technologies)

i. Legacy infrared / ECU units (affectively digital outputs from a chair that can drive 3rd party interfaces / devices. Could be as simple as an infrared door opener, a solenoid leg bag opener or more complex solutions, such as http://assistive.technology.proteor.com/product,120-environmental-control-unit,1402-keo-usa.php

ii. Current state-of-the-art is the connecting to a 3rd party device e.g. iPad that controls the home automation system

iii. Are there emerging standards that can be built in to a wheelchair system? E.g. a Bluetooth home automation profile (this has been talked about, but not released yet).

    Apple, Microsoft and Google are all talking about automated homes and healthcare platforms Note: a big driver for having connectivity on power chairs is health monitoring.

System redundancy – If an end user becomes dependant on their technology to live, how do they cope with technical failures in that technology? How do we ensure 24/7 access?

Context

There are numerous user interfaces, including a joystick input with multiple buddy buttons, head arrays, sip n puff, switch control and single button scanned input. How do we map this variety of inputs to what is available for 3rd party devices? This closely relates to Disability Type, as it is the interface between a user and their system.

There are numerous studies of how able-bodied users use their ICT, how do we identify the needs of disabled users and how do we expand this to encompass environmental / disability needs? This gives a driver of what to focus system capabilities towards.

In order to support certain needs are their additional programs / apps that can be developed / modified to meet specialist needs?

What are the legislative considerations, e.g. someone who is disabled has the same rights e.g. privacy. Consider applications that track your location, or collect medical information. How is this managed?

There are rules / legislation related to using technology e.g. when driving, in hospitals etc. when someone is dependent on it, how is it managed / do different rules apply?

What are the safety risks to end users of having technology? E.g. distractions when driving, system failures and accidentally put environment put in an unsafe condition.

Appendix G: Stakeholder Requirements

Technology Requirements

Requirement FR1

Requirement ID:	FR1
Requirement type:	Functionality
Description:	A technology shall not be a single solution to fit multiple needs.
Rationale:	Each end user will have different needs so it will not be possible to develop a single version of a technology that meets a range of abilities. It is important that a technology is an adaptable solution that can be customised.
Source:	Dynamic Controls
Fit criterion:	A variety of abilities are supported by the technology. The technology increases the Quality of Life for a range of tasks in varying environments.
Customer satisfaction:	4
Customer dissatisfaction:	4
Priority:	Must
Dependencies:	None
Conflicts:	None
Supporting Materials:	Dynamic Controls requirements specification.

Requirement UR1

Requirement ID:	UR1
Requirement type:	Usability
Description:	A technology shall allow users to gain confidence.
Rationale:	For the technology to be accepted by the user community, it shall not overwhelm the user.
Source:	Dynamic Controls
Fit criterion:	The user interface functionality is not overly complex and can be tailored to suit the user's abilities. As the user becomes accustomed to the interface, it can be enhanced with additional functionality.
Customer satisfaction:	3
Customer dissatisfaction:	3
Priority:	Could
Dependencies:	FR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement IR1

Requirement ID:	IR1
Requirement type:	Interoperability
Description:	A technology shall provide a bridge between the powerchair and daily tasks.
Rationale:	For the technology to be 'fit for purpose' it shall be fully integrated, so that it provides a solution that improves Quality of Life.
Source:	Dynamic Controls
Fit criterion:	A technology is integrated physically and electronically into a standard powerchair, so that no permanent modifications are made. A technology shall not interfere with another.
Customer satisfaction:	5
Customer dissatisfaction:	5
Priority:	Must
Dependencies:	FR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement RR1

Requirement ID:	RR1
Requirement type:	Reliability
Description:	A technology shall be robust against potential technical failures.
Rationale:	As the users be dependent on the technology in their daily lives, mechanisms to cope with technical failures shall be implemented.
Source:	Dynamic Controls
Fit criterion:	Suitable system redundancy exists so that there is at least one alternative interaction method should a technology fail. The user is not reliant upon one form of technology.
Customer satisfaction:	3
Customer dissatisfaction:	5
Priority:	Must
Dependencies:	FR1, IR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement RR2

Requirement ID:	RR2
Requirement type:	Reliability
Description:	A technology shall be accessible at any time.
Rationale:	The users of a technology will need to access 24 hours a day, 7 days a week, so the technologies cannot have downtime.
Source:	Dynamic Controls
Fit criterion:	A technology functions reliably irrespective of the time of day. The performance of the technology remains constant.
Customer satisfaction:	3
Customer dissatisfaction:	5
Priority:	Must
Dependencies:	FR1, IR1, RR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement PR1

Requirement ID:	PR1
Requirement type:	Performance
Description:	A technology shall conform to legislative guidelines for users with reduced physical ability.
Rationale:	It is important to consider the same rights of users with reduced physical ability as able-bodied users.
Source:	Dynamic Controls
Fit criterion:	A risk analysis conducted on a technology identifies no issues to the safety of the user. Privacy of any personal data obtained by the technology is addressed.
Customer satisfaction:	3
Customer dissatisfaction:	5
Priority:	Should
Dependencies:	SFR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement SFR1

Requirement ID:	SFR1
Requirement type:	Safety
Description:	A technology shall not present a safety risk to the users.
Rationale:	The users must not be subjected to any additional safety risks when using a technology.
Source:	Dynamic Controls
Fit criterion:	A technology functions safely without endangering the user. A risk analysis shows no identifiable issues to the user.
Customer satisfaction:	5
Customer dissatisfaction:	5
Priority:	Must
Dependencies:	FR1, IR1, RR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Framework Stakeholder Requirements

Requirement FR2

Requirement ID:	FR2
Requirement type:	Functionality
Description:	A framework shall map the variety of interaction methods for technologies to the abilities of the user.
Rationale:	Depending on their ability, the users will have preferences over the technology interaction method.
Source:	Dynamic Controls
Fit criterion:	A framework enables a list of technologies that can be integrated with powerchairs to be viewed. Only technologies that are suitable for the user's abilities are suggested by the framework.
Customer satisfaction:	3
Customer dissatisfaction:	3
Priority:	Must
Dependencies:	FR1, UR1, IR1, FR3.
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Requirement FR3

Requirement ID:	FR3
Requirement type:	Functionality
Description:	The needs of disabled users shall be encompassed in the design of a framework.
Rationale:	To ensure that a framework is suitable for the user community, it is imperative that the views of users with reduced physical ability are considered through a User Centred Design approach.
Source:	Dynamic Controls
Fit criterion:	The framework addresses the challenges currently encountered by users with reduced physical ability through the application of technology.
Customer satisfaction:	5
Customer dissatisfaction:	5
Priority:	Should
Dependencies:	UR1
Conflicts:	None
Supporting materials:	Dynamic Controls requirements specification.

Appendix H: SmartATRS Hierarchical Task Analysis

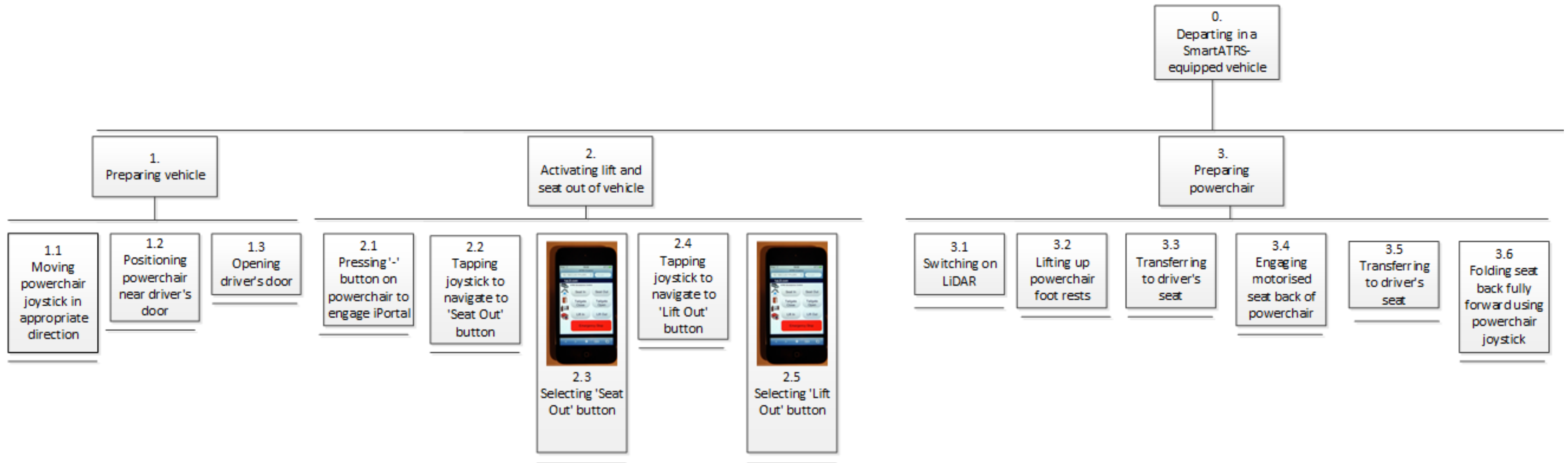


Figure 71: SmartATRS HTA (1)

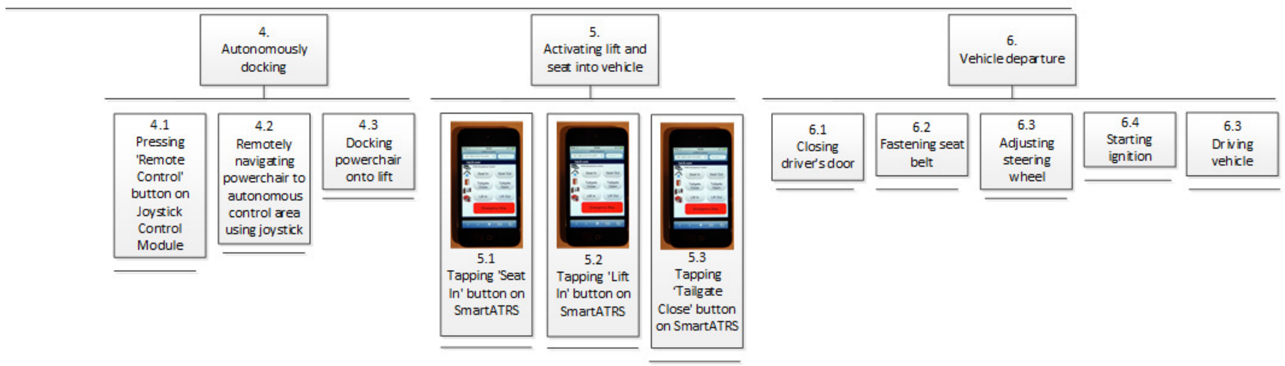


Figure 72: SmartATRS HTA (2)

Appendix I: Risk Assessment for Evaluation 1

1. Describe the Activity being Risk Assessed User Evaluation of SmartATRS for a research paper
2. Location(s) CG17 and the car park directly outside Christchurch House
3. Persons at potential Risk (e.g. consider specific types of individuals) Post Graduate student conducting the User Evaluation Participants of the User Evaluation Observers of the User Evaluation
4. Potential Hazards (e.g. list hazards without considering any existing controls): 1. Participants are operating moving adaptations (seat, lift and tailgate) installed in a vehicle, which are unfamiliar to them, potentially causing the adaptation to operate unsafely. 2. Participants standing too close to the moving adaptations whilst in operation, potentially causing injury to the participants. 3. Members of the public walking too close to the vehicle during the evaluation, potentially causing injury to the public and the adaptations. 4. Other vehicles driving too close to the vehicle during the evaluation, potentially causing injury to the student, participants and observers as well as damage to the adaptations. 5. The keyfobs could be dropped by the participants, damaging the keyfobs. 6. The Smartphone may be dropped by the participants, damaging the Smartphone. 7. The tailgate could be slammed shut, potentially damaging the tailgate. 8. If the participants touch the powerchair joystick whilst transferring into the powerchair, the powerchair may begin to move, potentially injuring participants.
5. Any Control Measures Already In Place: There are control measures already in place to address each numbered risk stated in section 4:

1. All participants will be sent a Briefing Document and instructions for the tasks being performed prior to evaluation day, so that they gain an understanding of what is required when operating the moving adaptions. The participants will also be briefed on the day before performing the tasks.
2. The area immediately surrounding the vehicle will be coned off and the participants will be advised not to stand too close to the moving adaptations.
3. The area immediately surrounding the vehicle will be coned off and any member of the public who stray too close will be informed to stand back.
4. The area immediately surrounding the vehicle will be coned off. The disabled parking space chosen for the evaluation is situated in a relatively quiet area of the carpark. The parking space has been reserved by Estates to ensure that it cannot be used by another vehicle. Any vehicle who drives too close will be informed to park elsewhere.
5. It will ensured that the keyfobs are attached to each participant by a lanyard prior to use. Therefore even if the participants let go of the keyfobs, they will not drop it.
6. The smartphone will be permanently attached to the powerchair using a mount. It will not be removed during operation and the participants will only use the Smartphone when seated in the powerchair.
7. It has been highlighted in the instructions that the tailgate must not be slammed shut. The participants will be informed a second time during the briefing.
8. The student take responsibility for ensuring that the powerchair is always switched off whilst participants are transferring into it. Therefore, even if the participants touch the joystick, the powerchair will not move.

6. Standards to be Achieved: (ACOPs, Qualifications, Regulations, Industry Guides, Suppliers instructions etc)

The participants will be following the User Evaluation pack produced by the student that has been tested to be safe.

7. Estimating the Residual Risk (e.g. remaining risk once existing control measures are taken into account)

Choose a category that best describes the degree of harm which could result from the hazard and then choose a category indicating what the likelihood is that a person(s) could be harmed.

	Slightly Harmful (e.g. minor injuries)	Harmful (e.g. serious but short-term injuries)	Extremely Harmful (e.g. fatality, long-term injury or incurable disease)
Highly Unlikely	Trivial Risk ☐	Tolerable Risk ☐	Moderate Risk ☐
Unlikely	Tolerable Risk ☒	Moderate Risk ☐	Substantial Risk ☐
Likely	Moderate Risk ☐	Substantial Risk ☐	Intolerable Risk ☐

8. Note the advice below on suggested actions and timescales:	
Risk (from No.7)	Action/Timescale
Trivial Risk ☐	No action is required and no records need to be kept.
Tolerable Risk ☒	No additional controls are required, although consideration may be given to an improvement that imposes no additional cost/s. Monitoring is required to ensure that the controls are maintained.
Moderate Risk ☐	Efforts should be made to reduce the risk, but the costs of prevention should be carefully measured and limited. Any new measures should be implemented within a defined period. Where the moderate risk is associated with extremely harmful consequences, further assessment may be necessary to establish more precisely the likelihood of harm as a basis for determining the need for improved control measures.

Substantial Risk ☐	Work should NOT commence until the risk has been reduced. Considerable resources may have to be allocated to reduce the risk. Where the risk involves work in progress, urgent action MUST be taken.
Intolerable Risk ☐	Work should not be started or continued until the risk has been reduced. If it is not possible to reduce the risk even with unlimited resources, work MUST remain prohibited.

9. If 'Moderate' 'Substantial' or 'Intolerable': What New Control Measures are to be Considered to reduce risk? N/A	10. Referred to: N/A	11. Date: N/A

12. Ensure those affected are informed of the Risks & Controls (Confirm how you have done this e.g. written instructions): Verbal instructions during the User Evaluation briefing					
13. Person who did Assessment:	Paul Whittington	14. Date:	13/12/13	15. Review Date:	N/A
16. Checked or Assisted By:	Huseyin Dogan	17. Date:	13/12/13	18. Review Date:	N/A

Appendix J: Evaluation 1 Documents

Ethics Checklist

Research Ethics Checklist

Status	Submitted

Researcher Details

Name	Paul Whittington
School	Design Engineering and Computing
Status	Postgraduate Research (PhD, MPhil, DProf, DEng)
Course / Research Centre	Software Systems Research Centre
Do you intend to apply for external funding to support this research project?	No

Project Details

Title	SmartATRS User Evaluation
Proposed Start Date	18/12/2013
Proposed End Date	18/12/2013
Supervisor	Huseyin Dogan

Summary (including detail on background methodology, sample, outcomes, etc.)
A User Evaluation will be conducted on the Automated Transport and Retrieval Syatem (ATRS) by comparing two types of Human Computer Interaction, wireless keyfobs and a Smartphone system, SmartATRS. This will take place with a vehicle installed with ATRS and thirteen participants will conduct five predefined tasks with ATRS using both methods of interaction. The participants will then be asked to complete a series of questionnaires about each method. The aim is to determine which method of interaction is the most usable for people with reduced finger dexterity. The feedback obtained through the questionnaires will be used in a Work in Progress paper on SmartATRS for the CHI 2014 conference.

External Ethics Review

Does your research require external review through the NHS National Research Ethics Service (NRES) or through another external Ethics Committee?	No

Research Literature

Is your research solely literature based?	No

Human Participants

Will your research project involve interaction with human participants as primary sources of data (e.g. interview, observation, original survey)?	Yes
Does your research specifically involve participants who are considered vulnerable (i.e. children, those with cognitive impairment, those in unequal relationships—such as your own students, prison inmates, etc.)?	No
Does the study involve participants age 16 or over who are unable to give informed consent (i.e. people with learning disabilities)? NOTE: All research that falls under the auspices of the Mental Capacity Act 2005 must be reviewed by NHS NRES.	No
Will the study require the co-operation of a gatekeeper for initial access to the groups or individuals to be recruited? (i.e. students at school, members of self-help group, residents of Nursing home?)	No
Will it be necessary for participants to take part in your study without their knowledge and consent at the time (i.e. covert observation of people in non-public places)?	No
Will the study involve discussion of sensitive topics (i.e. sexual activity, drug use, criminal activity)?	No

Are drugs, placebos or other substances (i.e. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	No

Will tissue samples (including blood) be obtained from participants? Note: If the answer to this question is 'yes' you will need to be aware of obligations under the Human Tissue Act 2004.	No

Could your research induce psychological stress or anxiety, cause harm or have negative consequences for the participant or researcher (beyond the risks encountered in normal life)?	No
Will your research involve prolonged or repetitive testing?	No
Will the research involve the collection of audio, photographic or video materials?	No
Will financial or other inducements (other than reasonable expenses and compensation for time) be offered to participants?	Yes

Please give a summary of the ethical issues and any action that will be taken to address these. Explain how you will obtain informed consent (and from whom) and how you will inform the participant about the research project

(i.e. participant information sheet).
All participants have been contacted prior to the User Evaluation and have sent their consent to particpate. The participants will also be provided with a briefing about SmartATRS and instructions on how to perform each task prior to the evaluation day.

Final Review

Will you have access to personal data that allows you to identify individuals OR access to confidential corporate or company data (that is not covered by confidentiality terms within an agreement or by a separate confidentiality agreement)?	No
Will your research involve experimentation on any of the following: animals, animal tissue, genetically modified organisms?	No
Will your research take place outside the UK (including any and all stages of research: collection, storage, analysis, etc.)?	No

Please use the below text box to highlight any other ethical concerns or risks that may arise during your research that have not been covered in this form.

Participant Information Sheet

Briefing Notes

- Welcome to the User Evaluation of SmartATRS. During the evaluation, I would like you to control the adaptations installed in my vehicle using the Automated Transport and Retrieval System (ATRS) by performing 5 tasks with:
    - Two Keyfobs
    - A Smartphone system on the powerchair by touch and joystick
- After completing the tasks, I would like you to complete questionnaires that I can use to evaluate for my research paper

An Introduction to the System

- ATRS comprises of a motorised driver's seat, tailgate and lift installed in the vehicle
- Keyfobs and SmartATRS control 7 functions of ATRS:
    - Seat In
    - Seat Out
    - Tailgate Open
    - Tailgate Close
    - Lift In
    - Lift Out
    - Emergency Stop
- When using the keyfobs, only the Lift In, Lift Out and Seat In functions will stop automatically. All of the other functions have to be stopped manually by pressing the appropriate function button a second time.

- When using the Smartphone, all functions are timed and there is no need to press the function buttons again to stop the function. The functions will stop automatically when the timer runs out.
- When using the Smartphone the buttons will change colour according to the current state as follows:
    - Grey = the function is not currently active
    - Blue = the function is currently active
    - Orange = the function cannot be selected

<u>Practicalities</u>

- The evaluation will be conducted as follows:
    1. All the information you need is contained within this pack
    2. Proceed outside to the car park and perform the evaluation
    3. Return inside to complete the questionnaires
    4. Enjoy a coffee and mince pie!

User Evaluation Pack

SmartATRS USER EVALUATION PACK V2

18th December 2013

PhD Student
Mr. Paul Whittington
Bournemouth University
Fern Barrow
POOLE, Dorset, UK BH12 5BB
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First Supervisor
Dr. Huseyin Dogan
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Second Supervisor
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Bournemouth University
Fern Barrow
POOLE, Dorset, UK BH12 5BB
kphalp@bournemouth.ac.uk

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SmartATRS USER EVALUATION TASKS

When completing the 5 tasks below, please use only your writing hand i.e. NOT BOTH HANDS. ***(This will provide a greater indication of any difficulties that a user with reduced finger dexterity would potentially experience).***

Please perform all of the tasks whilst seated in the powerchair.

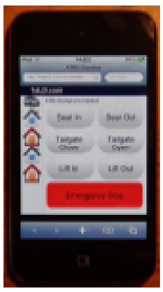
TASK 1 - SEAT OUT

1.1 Keyfobs

1. Using the Seat/Lift keyfob, press the grey button with the down arrow
2. Observe the seat driving out
3. Press the same button a second time to stop the seat when it is approximately 50cm above ground

1.2 SmartATRS

1. Press the 'Seat Out' button
2. Observe the seat driving out
3. Observe the seat stopping automatically when approximately 50cm above the ground



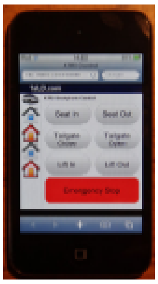
TASK 2 - TAILGATE OPEN

2.1 Keyfobs

1. Using the Tailgate keyfob, press and hold the '2' button until the tailgate is just over half-way open
2. Release the '2' button and observe the tailgate continuing to open until it is fully open

2.2 SmartATRS

1. Press the 'Tailgate Open' button
2. Observe the tailgate opening
3. Observe the pneumatic ram switching off automatically before the tailgate fully opens and the tailgate continuing to open until it is fully open



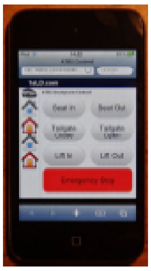
TASK 3 - LIFT OUT

3.1 Keyfobs

1. Using the Seat/Lift keyfob, press the yellow button on the right
2. Observe the lift driving out
3. Observe the lift stopping automatically when it reaches the ground

3.2 SmartATRS

1. Press the 'Lift Out' button
2. Observe the lift driving out
3. Observe the lift stopping automatically when it reaches the ground



TASK 4 – EMERGENCY STOP (LIFT IN AND SEAT IN)

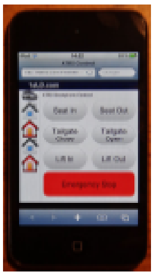
For this task, you will be operating two functions (Lift In and Seat In) simultaneously.

4.1 Keyfobs

1. Using the Seat/Lift keyfob, press the yellow button on the left to drive the lift in
2. Immediately press the grey button with the up arrow to drive the seat in
3. Observe the lift and seat driving into the vehicle
4. When 'Stop Lift!' or 'Stop Seat!' is said by Jane, stop the requested function by pressing the appropriate Lift In or Seat In button immediately
5. Observe either the seat or lift stopping immediately

4.2 SmartATRS

1. Press the 'Lift In' button
2. Immediately press the 'Seat In' button
3. Observe the lift and seat driving into the vehicle
4. When 'Stop Lift!' or 'Stop Seat!' is said by Jane, perform an emergency stop by pressing the red 'Emergency Stop' button
5. Observe both the seat and the lift stopping immediately



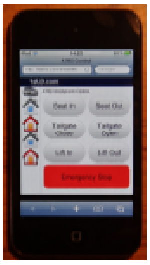
TASK 5 - TAILGATE CLOSE

5.1 Keyfobs

1. Using the Tailgate keyfob, press and hold the '1' button until the tailgate is just over half-way closed
2. Release the '1' button and observe the tailgate continuing to shut until it is fully closed. **The tailgate must not slam shut too hard!**

5.2 SmartATRS

1. Press the 'Tailgate Close' button
2. Observe the tailgate closing
3. Observe the pneumatic ram switching off before the tailgate closes and the tailgate continuing to shut until it is fully closed



TASK 6 – SEAT OUT/SEAT IN

6.1 SmartATRS using Joystick

1. *Moving the joystick will navigate through the icons on the smartphone.* Repeatedly move the joystick to the right for less than 1 second until the 'Seat Out' button is highlighted
2. Move the joystick forward for less than 1 second
3. Observe the seat driving out
4. Observe the seat stopping automatically when approximately 50cm above the ground
5. Move the joystick to the left for less than 1 second until the 'Seat In' button is highlighted
6. Move the joystick forward for less than 1 second
7. Observe the seat driving in
8. Observe the seat stopping automatically when it is stowed inside the car

SmartATRS USER EVALUATION QUESTIONNAIRES

When completing the following questionnaires, please imagine that you have reduced finger dexterity and are attempting to use the keyfobs and SmartATRS to operate the seat, tailgate, lift and emergency stop functions. Consider the difficulties that such a disabled user would encounter when using both methods.

Contact Details

First Name:	
Surname:	
Email Address:	

This questionnaire is fully anonymised.

User Profile

What age group do you belong to?

☐ <20 ☐ 20-30 ☐ 31-40 ☐ 41-50 ☐ 50+

What is your gender?

☐ Male ☐ Female

What is your educational background?

☐ Student ☐ Lecturer/Academic ☐ Administration ☐ Student Support ☐ Other

Are you colour blind?

☐ Yes ☐ No

SmartATRS USER EVALUATION QUESTIONNAIRES

When completing the following questionnaires, please imagine that you have reduced finger dexterity and are attempting to use the keyfobs and SmartATRS to operate the seat, tailgate, lift and emergency stop functions. Consider the difficulties that such a disabled user would encounter when using both methods.

Contact Details

First Name:	
Surname:	
Email Address:	

This questionnaire is fully anonymised.

User Profile

What age group do you belong to?

☐ <20 ☐ 20-30 ☐ 31-40 ☐ 41-50 ☐ 50+

What is your gender?

☐ Male ☐ Female

What is your educational background?

☐ Student ☐ Lecturer/Academic ☐ Administration ☐ Student Support ☐ Other

Are you colour blind?

☐ Yes ☐ No

SmartATRS USER EVALUATION – USING KEYFOBS

	Strongly disagree				Strongly agree
1. I think that I would frequently like to use the keyfobs	1	2	3	4	5
2. I found the keyfobs unnecessarily complex	1	2	3	4	5
3. I thought the keyfobs were easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use the keyfobs	1	2	3	4	5
5. I found the various functions on the keyfobs were well integrated	1	2	3	4	5
6. I thought that the Emergency Stop feature of the keyfobs was safe	1	2	3	4	5
7. I would imagine that most people would learn to use the keyfobs very quickly	1	2	3	4	5
8. I found the keyfobs very cumbersome to use	1	2	3	4	5
9. I felt very confident using the keyfobs	1	2	3	4	5
10. I needed to learn a lot of things before I could get going using the keyfobs	1	2	3	4	5

Other Comments:

SmartATRS USER EVALUATION – USING SmartATRS BY TOUCH

	Strongly disagree				Strongly agree
1. I think that I would frequently like to use SmartATRS by touch	1	2	3	4	5
2. I found using SmartATRS by touch unnecessarily complex	1	2	3	4	5
3. I thought using SmartATRS by touch was easy	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use SmartATRS by touch	1	2	3	4	5
5. I found the various functions of SmartATRS when using touch were well integrated	1	2	3	4	5
6. I thought that the Emergency Stop feature was safe when using SmartATRS by touch	1	2	3	4	5
7. I would imagine that most people would learn to use SmartATRS by touch very quickly	1	2	3	4	5
8. I found using SmartATRS by touch very cumbersome	1	2	3	4	5
9. I felt very confident using the SmartATRS by touch	1	2	3	4	5
10. I needed to learn a lot of things before I could get going using SmartATRS by touch	1	2	3	4	5

Other Comments:

10

SmartATRS USER EVALUATION – USING SmartATRS BY JOYSTICK

	Strongly disagree				Strongly agree
	1	2	3	4	5
1. I think that I would frequently like to use SmartATRS by joystick					
2. I found using SmartATRS by joystick unnecessarily complex					
3. I thought using SmartATRS by joystick was easy					
4. I think that I would need the support of a technical person to be able to use SmartATRS by joystick					
5. I found the various functions of SmartATRS when using the joystick were well integrated					
6. I thought that the Emergency Stop feature of SmartATRS was safe when using the joystick					
7. I would imagine that most people would learn to use SmartATRS by joystick very quickly					
8. I found using SmartATRS by joystick very cumbersome					
9. I felt very confident using the SmartATRS by joystick					
10. I needed to learn a lot of things before I could get going using SmartATRS by joystick					

Other Comments:

11

WORKLOAD MEASUREMENT QUESTIONNAIRE
OPERATING ATRS USING KEYFOBS

Please put a cross on each scale at the point which most reflects how much workload you experienced when using the keyfobs to operate ATRS. When completing the questionnaire, please imagine that you have reduced finger dexterity and are attempting to use the keyfobs to operate the seat, tailgate, lift and emergency stop functions. Consider the difficulties that such a disabled user would encounter. I am most interested in your first reaction to the amount of workload you experienced.

Name:	Task: Operating ATRS using keyfobs	Date: 18/12/2013

Mental Demand — How mentally demanding was using the keyfobs?

Very Low — Very High

Physical Demand — How physically demanding was using the keyfobs?

Very Low — Very High

Temporal Demand — How hurried or rushed was the Emergency Stop task using the keyfobs?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish the tasks?

Very Low — Very High

Frustration — How irritated were you using the keyfobs?

Very Low — Very High

Other Comments:

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WORKLOAD MEASUREMENT QUESTIONNAIRE
OPERATING ATRS USING SmartATRS BY TOUCH

Please put a cross on each scale at the point which most reflects how much workload you experienced when using SmartATRS to operate ATRS by touch. When completing the questionnaire, please imagine that you have reduced finger dexterity and are attempting to use SmartATRS by touch to operate the seat, tailgate, lift and emergency stop functions. Consider the difficulties that such a disabled user would encounter. I am most interested in your first reaction to the amount of workload you experienced.

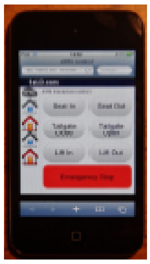
Name:	**Task:** Operating ATRS using SmartATRS by touch	**Date:** 18/12/2013

Mental Demand — How mentally demanding was using SmartATRS by touch?

Very Low — Very High

Physical Demand — How physically demanding was using SmartATRS by touch?

Very Low — Very High



Temporal Demand — How hurried or rushed was the Emergency Stop task using SmartATRS by touch?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish the tasks?

Very Low — Very High

Frustration — How irritated were you using SmartATRS by touch?

Very Low — Very High

Other Comments:

WORKLOAD MEASUREMENT QUESTIONNAIRE
OPERATING ATRS USING SmartATRS BY JOYSTICK

Please put a cross on each scale at the point which most reflects how much workload you experienced when using SmartATRS to operate ATRS by joystick. When completing the questionnaire, please imagine that you have reduced finger dexterity and are attempting to use SmartATRS by joystick to operate the seat, tailgate, lift and emergency stop functions. Consider the difficulties that such a disabled user would encounter. I am most interested in your first reaction to the amount of workload you experienced.

Name:	Task: Operating ATRS using SmartATRS by joystick	Date: 18/12/2013

Mental Demand — How mentally demanding was using SmartATRS by joystick?

Very Low — Very High

Physical Demand — How physically demanding was using SmartATRS by joystick?

Very Low — Very High

Temporal Demand — How hurried or rushed was the Emergency Stop task using SmartATRS by joystick?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish the tasks?

Very Low — Very High

Frustration — How irritated were you using SmartATRS by joystick?

Very Low — Very High

Other Comments:

General Feedback:

Thank you for participating in my User Evaluation. I very much appreciate your help. You can now enjoy a well-deserved coffee and mince pie!

Appendix K: Evaluation 2 Documents

Ethics Checklist

Bournemouth University

Research Ethics Checklist

Reference Id	9086
Status	Submitted

Researcher Details

Name	Paul Whittington
School	Faculty of Science & Technology
Status	Postgraduate Research (PhD, MPhil, DProf, DEng)
Course	Postgraduate Research
Have you received external funding to support this research project?	No

Project Details

Title	SmartATRS simulation
Proposed Start Date	14/10/2015
Proposed End Date	16/10/2015

Summary (including detail on background methodology, sample, outcomes, etc.)
I will be visiting Victoria School in Poole to conduct experiments with post 16 students. The individual experiments will consist of asking the students to complete tasks using touch and head tracking interaction methods. Each experiment will last less than an hour and the student's assistant can attend if required. The experiments will take place in the school environment and authorisation has been obtained from the Head of Post 16. Following each experiment, each participant will be provided with an Amazon gift card to thank them for their help.

External Ethics Review

Does your research require external review through the NHS National Research Ethics Service (NRES) or	No

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through another external Ethics Committee?	

Research Literature

Is your research solely literature based?	No

Human Participants

Will your research project involve interaction with human participants as primary sources of data (e.g. interview, observation, original survey)?	Yes
Does your research specifically involve participants who are considered vulnerable (i.e. children, those with cognitive impairment, those in unequal relationships—such as your own students, prison inmates, etc.)?	No
Does the study involve participants age 16 or over who are unable to give informed consent (i.e. people with learning disabilities)? NOTE: All research that falls under the auspices of the Mental Capacity Act 2005 must be reviewed by NHS NRES.	No
Will the study require the co-operation of a gatekeeper for initial access to the groups or individuals to be recruited? (i.e. students at school, members of self-help group, residents of Nursing home?)	Yes
Will it be necessary for participants to take part in your study without their knowledge and consent at the time (i.e. covert observation of people in non-public places)?	No
Will the study involve discussion of sensitive topics (i.e. sexual activity, drug use, criminal activity)?	No

Are drugs, placebos or other substances (i.e. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	No

Will tissue samples (including blood) be obtained from participants? Note: If the answer to this question is 'yes' you will need to be aware of obligations under the Human Tissue Act 2004.	No

Could your research induce psychological stress or anxiety, cause harm or have negative consequences for the participant or researcher (beyond the risks encountered in normal life)?	No
Will your research involve prolonged or repetitive testing?	No
Will the research involve the collection of audio materials?	Yes
Is this audio collection solely for the purposes of transcribing/summarising and will not be used in any outputs (publication, dissemination, etc.) and will not be made publicly available?	Yes

Will your research involve the collection of photographic or video materials?	Yes
Will financial or other inducements (other than reasonable expenses and compensation for time) be offered to participants?	Yes

Please explain below why your research project involves the above mentioned criteria (be sure to explain why the sensitive criterion is essential to your project's success). Give a summary of the ethical issues and any action that will be taken to address these. Explain how you will obtain informed consent (and from whom) and how you will inform the participant(s) about the research project (i.e. participant information sheet). A sample consent form and participant information sheet can be found on the Research Ethics website.
The research will be conducted with students between the ages of 16 and 19, therefore some will be classed as vulnerable. Informed consent will be obtained from Angus Collins, Head of Post 16, rather than the individual students. A participant information sheet will be given to each student prior to the interview. The research needs to be conducted at Victoria School, as this is the local special educational needs school. The feedback from the students could not be obtained from any other type of environment. The study requires the cooperation of the Victoria School reception and Angus Collins to allow myself and my Learning Support Assistant (Jane Merrington) onto the site. We will complete the necessary signing in procedure for Fire Regulations. The simulation will be video recorded for use in data analysis and to calculate the time taken for the participants to perform certain tasks.

Final Review

Will you have access to personal data that allows you to identify individuals OR access to confidential corporate or company data (that is not covered by confidentiality terms within an agreement or by a separate confidentiality agreement)?	Yes

Please explain below why your research requires the collection of personal data. Describe how you will anonymize the personal data (if applicable). Describe how you will collect, manage and store the personal data (taking into consideration the Data Protection Act and the 8 Data Protection Principles). Explain how you will obtain informed consent (and from whom) and how you will inform the participant about the research project (i.e. participant information sheet).
The experiment will consist of obtaining personal data about the participant's disability and contact details (if they would wish to be involved with future experimentations). Both types of data are vital for future research. Informed consent will be obtained from Angus Collins and the participants will be provided with participant information sheets.

Will your research involve experimentation on any of the following: animals, animal tissue, genetically modified organisms?	No
Will your research take place outside the UK (including any and all stages of research: collection, storage, analysis, etc.)?	No

Please use the below text box to highlight any other ethical concerns or risks that may arise during your research

Consent Form

Full title of project: SmartATRS simulation at Victoria School

Name, position and contact details of researcher: Mr Paul Whittington, PhD Student, Poole House, Bournemouth University (paul.whittington@bournemouth.ac.uk)

Name, position and contact details of supervisor: Dr Huseyin Dogan, Poole House, Bournemouth University (hdogan@bournemouth.ac.uk)

Please Initial Here

I confirm that I have read and understood the participant information sheet for the above research project and have had the opportunity to ask questions.	
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason and without there being any negative consequences. In addition, should I not wish to answer any particular question(s), complete a test or give a sample, I am free to decline.	
I give permission for members of the research team to use my identifiable information for the purposes of this research project.	

I agree to take part in the above research project.	

________________________________ ________________ ______________________________________

Name of Participant Date Signature

Mr Paul Whittington____________ 14/10/2015_____ ______________________

Name of Researcher Date Signature

Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the participant information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be kept with the project's main documents which must be kept in a secure location.

User Evaluation Pack

BOOT (TAILGATE) OPENING

Experiment

As we can't use a real car at this stage to bring the seat and lift in and out, and open and close the boot (tailgate), we are going to use video clips instead.

The experiment needs you to use the iPad with either your fingers or head to control the video clips of the seat and lift coming in and out, and the boot (tailgate) opening and closing.

PRACTICE

Fingers

1. Touch the 'Seat Out' button on the iPad.
2. Watch a video playing on the screen.

Head

1. Look at the iPad and watch the green vertical band moving from left to right.
2. When the green band is over the 'Seat Out' button, move your head sideways to stop the green band from moving.
3. Move your head sideways again to stop the green line on the button.

   (The green band will now change to a horizontal position moving from top to bottom)
4. When the green band is over the 'Seat Out' button, move your head sideways to stop the green band from moving.
5. Move your head sideways again to stop the green line on the button.

   (The button will turn blue)
6. Watch the video on the screen of the seat coming out (until the seat stops by itself near to the ground).

Preferred head movement

1

LIFT GOING IN WITH AN EMERGENCY STOP

Fingers

Press the 'Lift In' button on the iPad and watch the video on the screen of the lift coming out.

When 'STOP!' is said by Jane:

Touch the red 'Emergency Stop' button (as quick as you can) and watch the video of the lift stop.

Head

Look at the iPad and using head movements, select the 'Lift In' button and watch the video on the screen of the lift coming in.

When 'STOP!' is said by Jane:

Look at the iPad and using head movements, select the red 'Emergency Stop' button (as quick as you can) and watch the video of the lift stop.

QUESTIONS

First Name:	
Surname:	
Email Address:	

How old are you?

Are you?

☐ Male ☐ Female

Are you colour blind?

☐ Yes ☐ No

What is your disability?

Do you have finger dexterity impairment?

☐ Yes ☐ No

Do you work anything using head movements?

Would you like to take part in future experiments?

☐ Yes ☐ No

USING YOUR FINGERS TO CONTROL THE IPAD

	No		Not sure		Yes
1. I would always use my fingers to press the buttons on the iPad	1	2	3	4	5
2. I found pressing the buttons on the iPad with my fingers complicated	1	2	3	4	5
3. I thought pressing the buttons on the iPad with my fingers was easy	1	2	3	4	5
4. I think that I would need someone to show me how to press the buttons on the iPad with my fingers	1	2	3	4	5
5. I found choosing which button to press on the iPad easy	1	2	3	4	5
6. I thought that pressing the Emergency Stop button was easy	1	2	3	4	5
7. I think that most people would learn to press the buttons on the iPad with their fingers very quickly	1	2	3	4	5
8. I found choosing which button to press on the iPad very difficult	1	2	3	4	5
9. I felt very happy using my fingers to press the buttons on the iPad	1	2	3	4	5
10. I needed to learn a lot of things before I could press the buttons on the iPad with my fingers	1	2	3	4	5

USING HEAD MOVEMENTS TO CONTROL THE IPAD

	No		Not sure		Yes
	1	2	3	4	5
1. I would always use head movements to control the buttons on the iPad					
2. I found using head movements to make the buttons on the iPad work complicated					
3. I thought that using head movements to work the iPad was easy					
4. I think that I would need someone to show me how to use head movements to work the buttons on the iPad					
5. I found choosing which button to work on the iPad using head movements easy					
6. I thought that choosing the Emergency Stop button using head movements was easy					
7. I think that most people would learn to use head movements to work the iPad very quickly					
8. I found choosing which button to work on the iPad using head movements difficult					
9. I felt very happy using head movements to work the buttons on the iPad					
10. I needed to learn a lot of things before I could use head movements to work the buttons on the iPad					

Would you like to say anything else?

USING HEAD MOVEMENTS TO CONTROL THE IPAD

	No		Not sure		Yes
1. I would always use head movements to control the buttons on the iPad	1	2	3	4	5
2. I found using head movements to make the buttons on the iPad work complicated	1	2	3	4	5
3. I thought that using head movements to work the iPad was easy	1	2	3	4	5
4. I think that I would need someone to show me how to use head movements to work the buttons on the iPad	1	2	3	4	5
5. I found choosing which button to work on the iPad using head movements easy	1	2	3	4	5
6. I thought that choosing the Emergency Stop button using head movements was easy	1	2	3	4	5
7. I think that most people would learn to use head movements to work the iPad very quickly	1	2	3	4	5
8. I found choosing which button to work on the iPad using head movements difficult	1	2	3	4	5
9. I felt very happy using head movements to work the buttons on the iPad	1	2	3	4	5
10. I needed to learn a lot of things before I could use head movements to work the buttons on the iPad	1	2	3	4	5

Would you like to say anything else?

USING YOUR FINGERS TO CONTROL THE IPAD

Please put a cross on each scale to show how difficult you found pressing the buttons with your fingers to control the iPad.

Name:	Task: Using your fingers to control the iPad	Date: 14/10/2015

How much did you have to think to use your fingers to press the buttons?

Not much — Very much

How hard was it to move your fingers to press the buttons?

Not hard — Very hard

How quickly were you able to press the Emergency Stop button using your fingers?

Not very quickly — Very quickly

Were you able to do what you were asked to do with your fingers?

Yes — No

How hard was it to press the buttons with your fingers?

Easy — Very hard

How frustrating did you find it pressing the buttons with your fingers?

Not much — Very much

Would you like to say anything else?

USING HEAD MOVEMENTS TO CONTROL THE IPAD

Please put a cross on each scale to show how difficult you found pressing the buttons with your fingers to control the seat, lift and boot.

Name:	Task: Using head movements to control the iPad	Date: 14/10/2015

How much did you have to think to use head movements to work the buttons?

Not much — Very much

How hard was it to use head movements to work the buttons?

Not hard — Very hard

How quickly were you able to work the Emergency Stop button using head movements?

Not very quickly — Very quickly

Were you able to do what you were asked to do with head movements?

Yes — No

How hard was it to work the buttons with head movements?

Easy — Very hard

How frustrating did you find it working the buttons with head movements?

Not much — Very much

Would you like to say anything else?

Thank you for helping with my experiment!

9

Appendix K: SmartDisability Elements

Disabilities Element

	Disabilities										
Impairments	Acquired Brain Injury	Brittle Bone Disease	Cerebral Palsy	Multiple Sclerosis	Muscular Dystrophy	Osteoarthritis	Parkinson's Disease	Poliomyelitis	Spina Bifida	Spinal Cord Injury	Stroke
Joints											
Limited neck movement	✓	✓	✓			✓		✓			✓
Limited shoulder movement	✓	✓	✓			✓		✓			✓
Limited elbow movement	✓	✓	✓			✓		✓			✓
Limited wrist movement	✓	✓	✓			✓		✓			✓
Limited finger dexterity	✓	✓	✓			✓		✓			✓
Limited ankle movement	✓	✓	✓			✓		✓			✓
Joint hypermobility		✓									
Joint dislocation		✓									
Scoliosis			✓								
Muscles											
Contractures	✓		✓	✓	✓			✓			✓
Dyskenesia			✓	✓			✓				
Atrophy				✓	✓	✓		✓	✓	✓	✓
Paraplegia	✓		✓	✓	✓	✓		✓	✓	✓	✓
Quadraplegia / tetraplegia	✓		✓	✓				✓		✓	
Hemiparesis	✓		✓					✓			✓
Vision											
Visual	✓		✓	✓							✓
Cataracts					✓						
Sensory											
Dizziness			✓								
Speech			✓				✓				

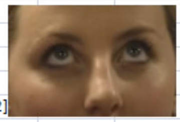
Reference Key

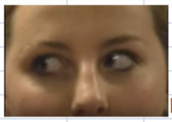
✓ (red)	Andrews,R., 2014. Disabling conditions and ICF measures [Microsoft Excel]. Cambridge: Addenbrooke's Hospital. Unpublished.
✓ (purple)	Healthline Networks Inc, 2015. *Polio: Types, Causes and Symptoms* [online]. San Francisco: Healthline Networks Inc. Available from: http://www.healthline.com/health/poliomyelitis [Accessed 9 December 2015].
✓ (black)	Whittington, P., Dogan, H. and Phalp, K. (2015) SmartPowerchair: to boldly go where a powerchair has not gone before. Ergonomics & Human Factors 2015, Daventry, UK, 13-16 April 2015. 233-240. CRC Press, London, UK.
✓ (blue)	Experimentation observations

Range of Movement Element

	Associated ROM								
Resulting Impairments	Eye	Mouth	Voice	Neck	Shoulder	Elbow	Wrist	Hand	Ankle
Joints									
Limited neck movement				✓					
Limited shoulder movement					✓				
Limited elbow movement						✓			
Limited wrist movement							✓		
Limited finger dexterity								✓	
Limited ankle movement									✓
Joint hypermobility					✓	✓	✓	✓	✓
Joint dislocation				✓	✓	✓	✓	✓	✓
Twisted spine				✓	✓				
Muscles									
Contractures		✓		✓	✓	✓	✓	✓	✓
Dyskenesia	✓	✓		✓	✓	✓	✓	✓	✓
Atrophy		✓		✓	✓	✓	✓	✓	✓
Paraplegia									✓
Quadraplegia / tetraplegia				✓	✓	✓	✓	✓	✓
Hemiparesis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vision									
Visual	✓								
Cataracts	✓								
Sensory									
Dizziness	✓	✓		✓	✓	✓	✓	✓	✓
Speech		✓	✓						

Movement Characteristics Element

[2] 

 [2]

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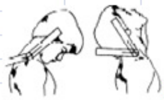
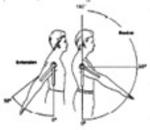
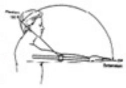
 [1]

[1] 

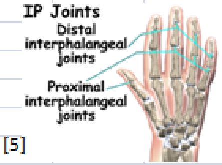
 [1]

[1]

 [1]

ROM Characteristic	Measurement Type		
	Max Degrees	Boolean	Max Percentage
Eye [2]			
Gaze up		Y/N	
Gaze down		Y/N	
Gaze left		Y/N	
Gaze right		Y/N	
Blinking		Y/N	
Mouth [4]			
Suck		Y/N	
Blow		Y/N	
Bite tongue		Y/N	
Move tongue left		Y/N	
Move tongue right		Y/N	
Smiling		Y/N	
Voice [1]			
Speech intelligability			100
Neck [3]			
Extension (chin up)	60		
Flexion (chin down)	50		
Rotation left	80		
Rotation right	80		
Shoulder [3]			
Flexion left	90		
Flexion right	90		
Elbow [3]			
Lateral left	90		
Lateral right	90		
Wrist [3]			
Radial (inwards) left	20		
Radial (inwards) right	20		
Ulnar (outwards) left	30		
Ulnar (outwards) right	30		
Flexion (down) left	60		
Flexion (down) right	60		
Extension (up) left	60		
Extension (up) right	60		

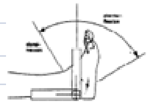
Movement Characteristics Element (cont.)



[5]

Hand [3]			
Digit 2 left IP	90		
Digit 3 left IP	90		
Digit 4 left IP	90		
Digit 5 left IP	90		
Digit 2 right IP	90		
Digit 3 right IP	90		
Digit 4 right IP	90		
Digit 5 right IP	90		
Thumb left IP	90		
Thumb right IP	90		
Ankle [3]			
Plantar flexion (down) left	40		
Plantar flexion (down) right	40		

[1]



[1]

References

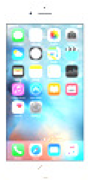
[1]	Bowen, C., 2015. *The proportion of a speaker's output that a listener can readily understand* [online]. Wentworth Falls, NSW: speeech-language-therapy dot com. Available from: http://www.speech-language-therapy.com/index.php?option=com_content&view=article&id=29:admin&catid=11:admin&Itemid=117 [Accessed 7 December 2015].
[2]	entukvideo, 2009. *Ocular Range of Motion and Ocular Alignment* [video, online]. Available from: https://www.youtube.com/watch?v=tQT0f1AVNmAb [Accessed 7 December 2015].
[3]	Washington State Department of Social and Health Services, 2013. *Range of Joint Motion Evaluation Chart* [online].
[4]	Whittington, P., Dogan, H. and Phalp, K. (2015a) Evaluating the Usability of an Automated Transport and Retrieval System. The 5th International Conference on Pervasive and Embedded Computing and Communication Systems, Angers, France, 11-13 February 2015. 59-66. Science and Technology Press, Lisbon, Portugal.
[5]	Medical Multimedia Group, LLC., 2015. *Hand Anatomy: A Patient's Guide to Hand Anatomy* [online]. Missoula, MT: Medical Multimedia Group, LLC. Available from: http://www.eorthopod.com/hand-anatomy/topic/157 [Accessed 14 December 2015].

Interaction Mediums Element

Associated Characteristic	Interaction Mediums									
	Joystick [1]	Voice [6]	Head [3]	Eye [2]	Sip n Puff [4]	Foot [4]	Chin [4]	Fingers [4]	Gesture [5]	Brain activity [8]
Eye										
Gaze up				■						■
Gaze down				■						■
Gaze left				■						■
Gaze right				■						■
Blinking				■						■
Mouth										
Suck					■					■
Blow					■					■
Bite tongue										■
Move tongue left										■
Move tongue right										■
Smiling										■
Voice										
Speech intelligability		■								
Neck										
Extension (chin up)			■				■	■		
Flexion (chin down)			■				■	■		
Rotation left			■				■	■		
Rotation right			■				■	■		
Shoulder										
Flexion left	■							■	■	
Flexion right	■							■	■	
Elbow										
Lateral left	■							■	■	
Lateral right	■							■	■	
Wrist										
Radial (inwards)left	■							■	■	
Ulnar (outwards) left	■							■	■	
Ulnar (outwards) right	■							■	■	
Flexion (down) left	■							■	■	
Flexion (down) right	■							■	■	
Extension (up) left	■							■	■	
Extension (up) right	■							■	■	
Hand										
Digit 2 left IP	■							■	■	
Digit 3 left IP	■							■	■	
Digit 4 left IP	■							■	■	
Digit 5 left IP	■							■	■	
Digit 2 right IP	■							■	■	
Digit 3 right IP	■							■	■	
Digit 4 right IP	■							■	■	
Digit 5 right IP	■							■	■	
Thumb left IP	■							■	■	
Thumb right IP	■							■	■	
Ankle										
Plantar flexion (down) left						■				
Plantar flexion (down) right						■				

Technologies Element

Interaction Mediums	Technology								
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]	Built-in Eye Tracking [4]	Built-in Head Tracking [6]	Stand-alone Eye Tracker [8]	Electroencephalogram [9]	Momentary Switches [10]	Rear View Camera [11]
Joystick									
Voice									
Head									
Eye									
Sip n Puff									
Foot									
Chin									
Fingers									
Brain activity									



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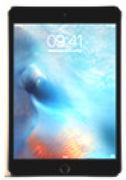

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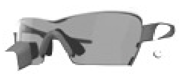
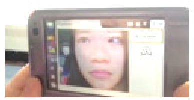
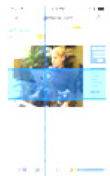


[3]

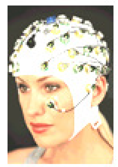


[4]



[7]

[8]



[9]

[10]

[11]

Tasks Element

Technologies	Tasks								
	Navigating powerchair [1]	Operating vehicle adaptations [1]	Operating cooking equipment [1][2]	Operating entertainment systems [1][2[	Operating home lifts [1]	Operating bathing equipment [3]	Operating food storage equipment [1]	Operating automatic cleaning equipment [1]	Operating hot drinks machines [2]
Smartphone									
Tablet									
Head Mounted Display									
Built-in Eye Tracker									
Stand-alone Eye Tracker									
Electroencephalogram									
Momentary Switches									
Rear View Camera									


[4]


[5]


[6]


[7]


[8]


[9]

[10]


[11]


[12]

Tasks Element (cont.)

Technologies	Tasks										
	Operating heating systems [1]	Operating light switches [1][2]	Operating automated curtains [1]	Operating automated windows [1]	Operating automated doors [1][2]	Operating automated shutters [2]	Operating intercom [2]	Operating electric beds [1][2]	Operating wall sockets [2]	Operating computers [2]	Outdoor Activities [1]
Smartphone											
Tablet											
Head Mounted Display											
Built-in Eye Tracker											
Stand-alone Eye Tracker											
Electroencephalogram											
Momentary Switches											
Rear View Camera											


[13]

[14]

[15]

[16]

[17]

[18]

[19]

[20]

[21]

[22]

[23]

Appendix L: SmartDisability Validation Documents

Ethics Checklist

Research Ethics Checklist

Bournemouth University

Reference Id	11930
Status	Approved
Date Approved	04/05/2016

Researcher Details

Name	Paul Whittington
School	Faculty of Science & Technology
Status	Postgraduate Research (MRes, MPhil, PhD, DProf, DEng)
Course	Postgraduate Research
Have you received external funding to support this research project?	No

Project Details

Title	Mobility Roadshow
Proposed Start Date of Data Collection	25/05/2016
Proposed End Date of Data Collection	28/05/2016

Summary - no more than 500 words (including detail on background methodology, sample, outcomes, etc.)

Huseyin Dogan, my assistant and I will be having an indoor stand at the Mobility Roadshow from 25th – 28th May at Silverstone showcasing my research. The purpose of attending is to validate my SmartDisability Framework and to perform experiments with smartglasses. Using paper copies of my framework, we will ask the visitors what their impairments are by ticking the relevant boxes in my framework. We will then use this to recommend technologies that they may find useful and suggest some tasks that they would be able to perform with the technologies. The visitors will then be given a questionnaire to complete about the framework. We will provide them with a list of the technologies that have been suggested by the framework. The smartglasses experiment will consist of the visitors trying them and seeing whether they can navigate through an interface. The visitors will then be given a separate questionnaire to complete about the glasses and we will reward the participants who complete both tasks, with a £10 Amazon voucher.

External Ethics Review

Does your research require external review through the NHS National Research Ethics Service (NRES) or through another external Ethics Committee?	No

Research Literature

Is your research solely literature based?	No

Human Participants

Will your research project involve interaction with human participants as primary sources of data (e.g. interview, observation, original survey)?	Yes
Does your research specifically involve participants who are considered vulnerable (i.e. children, those with cognitive impairment, those in unequal relationships—such as your own students, prison inmates, etc.)?	No
Does the study involve participants age 16 or over who are unable to give informed consent (i.e. people with learning disabilities)? NOTE: All research that falls under the auspices of the Mental Capacity Act 2005 must be reviewed by NHS NRES.	No
Will the study require the co-operation of a gatekeeper for initial access to the groups or individuals to be recruited? (i.e. students at school, members of self-help group, residents of Nursing home?)	No
Will it be necessary for participants to take part in your study without their knowledge and consent at the time (i.e. covert observation of people in non-public places)?	No
Will the study involve discussion of sensitive topics (i.e. sexual activity, drug use, criminal activity)?	No

Are drugs, placebos or other substances (i.e. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	No

Will tissue samples (including blood) be obtained from participants? Note: If the answer to this question is 'yes' you will need to be aware of obligations under the Human Tissue Act 2004.	No

Could your research induce psychological stress or anxiety, cause harm or have negative consequences for the participant or researcher (beyond the risks encountered in normal life)?	No
Will your research involve prolonged or repetitive testing?	No
Will the research involve the collection of audio materials?	No
Will your research involve the collection of photographic or video materials?	No
Will financial or other inducements (other than reasonable expenses and compensation for time) be offered to participants?	Yes

Please explain below why your research project involves the above mentioned criteria (be sure to explain why the sensitive criterion is essential to your project's success). Give a summary of the ethical issues and any action that will be taken to address these. Explain how you will obtain informed consent (and from whom) and how you will inform the participant(s) about the research project (i.e. participant information sheet). A sample consent form and participant information sheet can be found on the Research Ethics website.
£10 Amazon vouchers will be given to each participant to maximise the number of participants.

Final Review

Will you have access to personal data that allows you to identify individuals OR access to confidential corporate or company data (that is not covered by confidentiality terms within an agreement or by a separate confidentiality agreement)?	No
Will your research involve experimentation on any of the following: animals, animal tissue, genetically modified organisms?	No
Will your research take place outside the UK (including any and all stages of research: collection, storage, analysis, etc.)?	No

Please use the below text box to highlight any other ethical concerns or risks that may arise during your research that have not been covered in this form.

SmartDisability Framework Questionnaire

Which of the listed tasks could support your daily activities? How could they support you?

Did you know the recommended technologies could be useful?

Would you be able to use the interaction mediums and technologies that have been recommended to you? Would they be useful?

Would you like to take part in future research? If so, please write your name and email address below.

Would you like to say anything else?

Thank you for helping!

Appendix M: SmartDisability Elaborated Scenarios

Assumption: If there is no information about of a specific movement, then it is not affected by their disability.

1. Will

Will is 26 years old and has cerebral palsy. He already has a remote-controlled front door in his home. He has limited Range of Movement of his elbows, wrists, fingers and ankles. Will's disability results in joint dislocation, muscle contractures and atrophy (muscle wasting), and dystonia (involuntary movements). He cannot gaze left or right or blink. All mouth movements are possible to perform. Neck rotation is not possible for Will.

2. Joyce

Joyce is 75 years old and has arthritis and hemiparesis (weakness of the left side of her body). She currently drives a car with an automated tailgate and wheelchair lift. She has limited Range of Movement of her neck and wrists. Joyce is a left arm amputee and has muscle atrophy. She is not able to rotate or extend her neck up and down. Joyce's right hand is not affected.

3. Matt

Matt is 18 years old and has quadriplegia. He drives an adapted car. He has limited Range of Movement of his neck, shoulders, elbows, wrists, fingers and ankles. Matt' disability results in muscle contractures, atrophy and speech impairment. He is not able to rotate or extend his neck and has limited movement in his right arm. He cannot flex his right ankle. Matt cannot move his left thumb and right third digit. He can only extend both his left and right wrists. He is not able to plantar flex is right ankle.

4. **Becca**

Becca is 33 years old and has functional neuropathic spinal disease. She has no technology awareness. She has limited Range of Movement of her neck, shoulder, wrist, fingers and ankle. Becca has a prosthetic right leg and her disability results in contractures, dizziness, vision and speech impairments. She has limited movement in her right shoulder, left wrist and left fingers. She has limited movement in her right leg due to her prosthesis. Becca can suck but not blow. She is not able to rotate her neck left and extend it downwards.

5. **Anna**

Anna is 50 years old and has rheumatoid arthritis. She is already uses the following technologies; motorised can-opener, reclining bed, automated doors and has an adapted kitchen and bathroom in her home. She has limited Range of Movement of her neck, shoulder, elbows, wrists, fingers and ankles. Anna does not have elbows and her disability results in scoliosis, muscle contractures and atrophy, cataracts and dizziness. Anna wears arm splints for support. She cannot flex her right shoulder and left wrist. Digit four on her right hand is affected. She has limited tongue movement. She is not able move her wrists outwards but not flex. Anna can only flex her left shoulder. She cannot rotate her neck right and move her right elbow. Anna cannot plantar flex either of her ankles.

6. **Nick**

Nick is 67 years old and has Post Traumatic Stress Disorder. He is not aware of any assistive technologies. He has limited Range of Movement of his ankle. Nick is not able to walk and his disability results in dystonia, muscle contractures and speech impairment. He is not able to plantar flex in his left ankle. Due to his speech impairment, he cannot move his tongue left or right or bite it between his teeth.

Appendix N: SmartAbility Elements

Physical Conditions Element

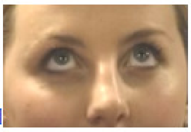
	Physical Conditions										
Specific Conditions	**Acquired Brain Injury**	**Brittle Bone Disease**	**Cerebral Palsy**	**Multiple Sclerosis**	**Muscular Dystrophy**	**Osteoarthritis**	**Parkinson's Disease**	**Poliomyelitis**	**Spina Bifida**	**Spinal Cord Injury**	**Stroke**
Joints											
Partial neck movement	✓	✓	✓			✓		✓			✓
Partial shoulder movement	✓	✓	✓			✓		✓			✓
Partial elbow movement	✓	✓	✓			✓		✓			✓
Partial wrist movement	✓	✓	✓			✓		✓			✓
Partial finger dexterity	✓	✓	✓			✓		✓			✓
Partial ankle movement	✓	✓	✓			✓		✓			✓
Joint hypermobility		✓									
Joint dislocation		✓									
Scoliosis			✓								
Muscles											
Contractures	✓		✓	✓	✓			✓			✓
Dyskenesia			✓	✓			✓				
Atrophy				✓	✓	✓		✓	✓	✓	✓
Paraplegia	✓		✓	✓	✓	✓		✓	✓	✓	✓
Quadraplegia / tetraplegia	✓		✓	✓				✓		✓	
Hemiparesis	✓		✓					✓			✓
Vision											
Visual	✓		✓	✓							✓
Cataracts					✓						
Sensory											
Dizziness			✓								
Speech			✓				✓				

Physical Conditions Element (cont.)

Reference Key

✓	Andrews,R., 2014. Disabling conditions and ICF measures [Microsoft Excel].
✓	Healthline Networks Inc, 2015. *Polio: Types, Causes and Symptoms* [online]. San Francisco: Healthline Networks Inc. Available from: http://www.healthline.com/health/poliomyelitis [Accessed 9 December 2015].
✓	Whittington, P., Dogan, H. and Phalp, K. (2015) SmartPowerchair: to boldly go where a powerchair has not gone before. Ergonomics & Human Factors 2015, Daventry, UK, 13-16 April 2015. 233-240. CRC Press, London, UK.
✓	Experimentation observations

Abilities Element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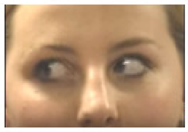
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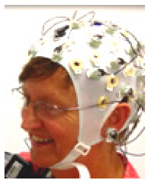


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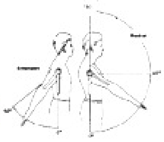
[1]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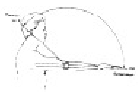
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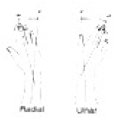
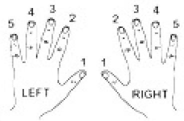


[1]


[1]

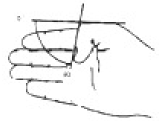
Abilities	Ease of Action		
	Easy	Difficult	Impossible
Eye [2]			
Looking upwards			
Looking downwards			
Looking left			
Looking right			
Blinking			
Seeing			
Mouth [4]			
Sucking			
Blowing			
Biting tongue			
Moving tongue left			
Moving tongue right			
Smiling			
Voice [1]			
Speaking clarity			
Neck [3]			
Moving neck upwards			
Moving neck downwards			
Moving neck left			
Moving neck right			
Shoulder [3]			
Lifting left shoulder			
Lifting right shoulder			
Elbow [3]			
Bending left elbow			
Bending right elbow			
Wrist [3]			
Moving left wrist inwards			
Moving right wrist inwards			
Moving left wrist outwards			
Moving right wrist outwards			
Moving left wrist downwards			
Moving right wrist downwards			
Moving left wrist upwards			
Moving right wrist upwards			

Abilities Element (cont.)



[5]

Hand [3]			
Bending left thumb			
Bending right thumb			
Bending second left finger			
Bending second right finger			
Bending third left finger			
Bending third right finger			
Bending fourth left finger			
Bending fourth right finger			
Bending fifth left finger			
Bending fifth right finger			
Ankle [3]			
Bending left ankle downwards			
Bending right ankle downwards			



[1]

[1]

References

[1]	Bowen, C., 2015. *The proportion of a speaker's output that a listener can readily understand* [online]. Wentworth Falls, NSW: speeech-language-therapy dot com. Available from: http://www.speech-language-therapy.com/index.php?option=com_content&view=article&id=29:admin&catid=11:admin&Itemid=117 [Accessed 7 December 2015].
[2]	entukvideo, 2009. *Ocular Range of Motion and Ocular Alignment* [video, online]. Available from: https://www.youtube.com/watch?v=tQT0f1AVNmAb [Accessed 7 December 2015].
[3]	Washington State Department of Social and Health Services, 2013. *Range of Joint Motion Evaluation*
[4]	Whittington, P., Dogan, H. and Phalp, K. (2015a) Evaluating the Usability of an Automated Transport and Retrieval System. The 5th International Conference on Pervasive and Embedded Computing and Communication Systems, Angers, France, 11-13 February 2015. 59-66. Science and Technology Press, Lisbon, Portugal.
[5]	ideallaedi, 2012. Archive for 'piano-promenades' category [Online]. Available from: https://ideallaedi.wordpress.com/category/piano-promenades/ [Accessed 29 July 2016]

Interaction Mediums Element

Ability:

● Mandatory

○ Non-mandatory

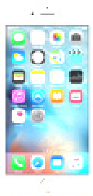
Abilities	Arm [10]	Brain [8]	Chin [4]	Eye [2]	Fingers [4]	Foot [4]	Hand [1]	Head [3]	Sip n Puff [4]	Tongue [10]	Voice [6]
Eye [2]											
Looking upwards	○	●	○	●	○	○	○	○	○	○	○
Looking downwards	○	●	○	●	○	○	○	○	○	○	○
Looking left	○	●	○	●	○	○	○	○	○	○	○
Looking right	○	●	○	●	○	○	○	○	○	○	○
Blinking	○	●	○	●	○	○	○	○	○	○	○
Seeing	●	○	○	●	●	○	●	●	●	○	○
Mouth [4]											
Sucking	○	○	○	○	○	○	○	○	●	○	○
Blowing	○	○	○	○	○	○	○	○	○	○	○
Biting tongue	○	●	○	○	○	○	○	○	○	●	○
Moving tongue left	○	●	○	○	○	○	○	○	○	●	○
Moving tongue right	○	●	○	○	○	○	○	○	○	●	○
Smiling	○	●	○	○	○	○	○	○	○	○	○
Voice [1]											
Speaking clarity	○	●	○	○	○	○	○	○	○	○	●
Neck [3]											
Moving neck upwards	○	○	●	○	○	○	○	●	○	○	○
Moving neck downwards	○	○	●	○	○	○	○	●	○	○	○
Moving neck left	○	○	●	○	○	○	○	●	○	○	○
Moving neck right	○	○	●	○	○	○	○	●	○	○	○

Technologies Element

Interaction Mediums	Technologies						
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]	Eye Tracker [4]	Head Tracker [6]	Electroencephalogram [9]	Switch [10]
Arm	■	□	■				□
Brain						■	
Chin							□
Eye	▲	▲	▲	▲	▲	▲	△
Fingers	■	■	■				□
Foot							□
Hand	■	□	■				□
Head				■	■		□
Sip n Puff	■	■					■
Tongue						■	■
Voice	◆	◆	◆				

<u>Actions</u>

- Using: ■ High agility; □ Low agility
- Seeing: ▲ High acuity; △ Low acuity
- Speaking: ◆ High clarity; ◇ Low clarity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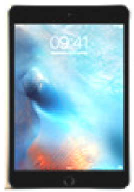
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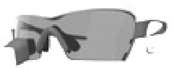
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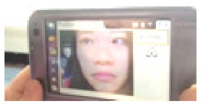
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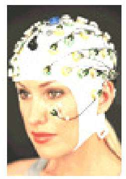
[6]


[7]


[8]

Technologies Element (cont.)

References

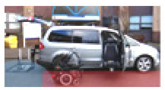
[1]	Apple Inc, 2016. *iPhone 6s: The only thing that's changed is everything* . [Online]. Cupertino, CA: Apple Inc. Available from: http://www.apple.com/uk/iphone/ [Accessed 06 January 2016].
[2]	Apple Inc, 2016. *iPad mini 4: Mighty. Small.* [Online]. Cupertino, CA: Apple Inc. Available from: http://www.apple.com/uk/ipad-mini-4/ [Accessed 06 January 2016].
[3]	Recon Instruments, 2016. *Recon JET: Smarter eyewear. Built by athletes for athletes.* [Online]. Vancover, BC: Recon Instruments. Available from: http://www.reconinstruments.com/products/jet/ [Accessed 06 January 2016].
[4]	Miluzzo, E., Wang, T. and Cambell, A.T, 2010. EyePhone: activating mobile phones with your eyes [Online]. In: MobiHeld '10 - 2010 ACM SIGCOMM Workshop on Networking, Systems, and Applications on Mobile Handhelds, New Delhi 30 August - 03 September 2010. New York NY: ACM. Available from: http://dl.acm.org/citation.cfm?id=1851328 [Accessed 08 January 2016].
[5]	Despoke, 2010. Eyephone: Operate A Cell Phone With Your Eyes. *Despoke* [Online]. 31 May 2010. Available from: http://www.despoke.com/2010/05/31/eyephone-operate-a-cell-phone-with-your-eyes/ [Accessed 08 January 2016].
[6]	Apple Inc, 2016. *iOS: Switch Control helps you navigate your iOS device* . [Online]. Cupertino, CA: Apple Inc. Available from: https://support.apple.com/en-gb/HT201370 [Accessed 06 January 2016].
[7]	Brain Products GmbH, 2016. *actiCAP - The third generation of active electrode* [Online]. Gilching: Brain Products GmbH. Available from: http://www.brainproducts.com/productdetails.php?id=4 [Accessed 06 January 2016].
[8]	Loughran, S.,2015.Alternative ways to control a power wheelchair. *ATandMe* [Online]. 31 July 2015. Available from: http://www.atandme.com/?p=950 [Accessed 06 January 2016].

Tasks Element

Interaction Mediums	Tasks						
	Navigating powerchair [1]	Operating vehicle adaptations [1]	Operating cooking equipment [1][2]	Operating entertainment systems [1][2]	Operating home lifts [1]	Operating bathing equipment [3]	Operating food storage equipment [1]
Arm		●	●	●	●	●	●
Brain	●	●	●	●	●	●	●
Chin	●	●	●	●	●	●	●
Eye	● ● ● ● ●	● ● ● ● ● ● ●	● ● ● ● ● ● ●	● ● ● ● ● ● ●	● ● ● ● ● ● ●	● ● ● ● ● ● ●	● ● ● ● ● ● ●
Fingers	● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●
Foot		●	●	●	●	●	●
Hand		●	●	●	●	●	●
Head		● ●	● ●	● ●	● ●	● ●	● ●
Sip n Puff	● ●	● ●	● ●	● ●	● ●	● ●	● ●
Tongue	● ●	● ●	● ●	● ●	● ●	● ●	● ●
Voice	● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●

Key
- ● Smartphone
- ● Tablet
- ● Head Mounted Display
- ● Eye Tracker
- ● Head Tracker
- ● Electroencephalogram
- ● Switches


[4]


[5]


[6]


[7]


[8]


[9]

Tasks Element (cont.)

Tasks							
Operating automatic cleaning equipment [1]	Operating hot drinks machines [2]	Operating heating systems [1]	Operating light switches [1][2]	Operating automated curtains [1]	Operating automated windows [1]	Operating automated doors [1][2]	Operating automated shutters [2]
●	●	●	●	●	●	●	●
●	●	●	●	●	●	●	●
●	●	●	●	●	●	●	●
● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●
● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●
●	●	●	●	●	●	●	●
●	●	●	●	●	●	●	●
● ●	● ●	● ●	● ●	● ●	● ●	● ●	● ●
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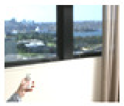
[11]


[12]


[13]


[14]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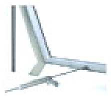
[16]


[17]


[18]

Tasks Element (cont.)

Tasks			
Operating intercom [2]	Operating electric beds [1][2]	Operating wall sockets [2]	Operating computers [2]
●	●	●	●
●	●	●	●
●	●	●	●
● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●	● ● ● ● ● ●
● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●
●	●	●	●
●	●	●	●
● ●	● ●	● ●	● ●
● ●	● ●	● ●	● ●
● ●	● ●	● ●	● ●
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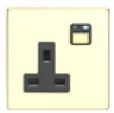
[19]


[20]


[21]


[22]

Appendix O: SmartAbility Data Dictionary

Keywords	Description/examples	Source	Thesis Section
Strong positive relationship	When one user-ability is strongly associated with another user-ability, i.e. the abilities will be performed simultaneously. E.g. a right elbow movement is strongly associated with a right shoulder movement.	Relationship concept adapted from the 'Roof' of QFD. (http://www.webducate.net/qfd/qfd.html) Observation from Evaluation 2	3.6.4
Positive relationship	When one user-ability is associated with another user-ability, i.e. the abilities could be performed simultaneously. E.g. Bending the left thumb could be associated with a left wrist movement.	Relationship concept adapted from the 'Roof' of QFD. (http://www.webducate.net/qfd/qfd.html) Observation from Evaluation 2	3.6.4

Mandatory ability	The ability required to operate an interaction medium successfully. E.g. a head interaction medium requires a left or right neck movement.	Feasibility Trial 5 and observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	5.6 7.2 7.3 7.4
High movement agility	Technologies that require precise body movements for successful operation. E.g. Smartphones require high levels of finger dexterity	Feasibility Trials 1 and 5 and observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	5.2 5.6 7.2 7.3 7.4
Low movement agility	Technologies that require less precise body movements for successful operation. E.g. Head activated switches require low levels of head movement.	Feasibility Trials 1 and 5 and observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	5.2 5.6 7.2 7.3 7.4
High visual acuity	Technologies that require clear sight for successful operation. E.g. Head Mounted Displays require the user to see clearly.	Feasibility Trials 1 and 5 and observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	5.2 5.6 7.2 7.3 7.4

Low visual acuity	Technologies that require less clear or no sight for successful operation. E.g. switches may not require the user to see clearly.	Feasibility Trials 1 and 5 and observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	5.2 5.6 7.2 7.3 7.4
Ability to speak	Technologies that require the user to speak E.g. Operating a smartphone by voice requires the user to speak	Suggestion from Validation Phase 3	9.4.2
Easy (Ability)	The user is able to perform the ability independently without exertion of significant physical effort.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4
Difficult (Ability)	The user is able to perform the ability independently but requires exertion of significant physical effort.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4
Impossible (Ability)	The user is not able to perform the ability independently.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4

Interaction Mediums (IM) / User Abilities Relationships (UAR)			
IM: • Arm **UAR**: • Lifting shoulders • Bending elbows • Moving wrists • Bending thumbs • Bending fingers	An arm interaction medium can either be controlled by shoulders (requiring >20° range), elbows (requiring >20° range), wrists (requiring >20° range in, >20° out, >20° up and down), thumbs (requiring >20° range), or fingers (requiring >20° range). E.g. an elbow activated switch.	Suggested by SmartDisability validation focus group.	8.4
IM: • Brainwave Detection **UAR**: • Looking • Blinking • Moving tongue • Biting tongue • Smiling • Speaking	A brainwave detection interaction medium can either be controlled by moving the eyes, blinking, tongue movements or smiling. E.g. EEG controlled by a right eye movement.	Feasibility Trial 1	5.2

IM: • Chin **UAR**: • Moving neck	A chin interaction medium can either be controlled by moving the neck (requiring >30° range up, >20° range down, 80° range left and right) E.g. A chin activated joystick operated by a downwards neck movement.	Literature reviews of assistive technologies	2.8
IM: • Eye **UAR**: • Looking • Blinking • Seeing	An eye-based interaction medium can be controlled by any direction of eye movement and also requires good vision (requiring 20:20). E.g. Eye Tracking operated with a left eye movement.	Literature reviews of assistive technologies	2.8
IM: • Fingers **UAR**: • Moving wrist • Bending thumb • Bending fingers	A finger based interaction medium can be controlled by moving the wrists (requiring >20° range in, >20° out, >20° up and down), and fingers (requiring >20° range). E.g. operating a smartphone by touch.	Observations from Evaluations 1, 2 and 3,	7.2 7.3 7.4
IM: • Foot **UAR**: • Bending ankles	A foot interaction medium can be controlled by either bending the left or right ankles downwards (requiring >20° range). E.g. a switch activated by the left foot to operate secondary controls on a vehicle.	Literature reviews of assistive technologies	2.8

IM: • Hand **UAR**: • Moving wrists	A hand-based interaction medium involves moving the wrists (requiring >20° range in, >20° out, >20° up and down). E.g. a switch activated by hand to open an automated door.	Literature reviews of assistive technologies	2.8
IM: • Head **UAR**: • Moving neck	A head-based interaction medium requires the neck to be moved (requiring >20° range up, >20° range down, 80° range left and right). E.g. a smartphone controlled by Head Tracking.	Observations from Evaluation 2	7.3
IM: • Suck and blow **UAR**: • Sucking • Blowing	A suck, blow interaction medium the ability to suck and blow mouth movement E.g. Sip 'n' Puff to control a tablet	Literature reviews of assistive technologies	2.8
IM: • Tongue **UAR**: • Biting tongue • Moving tongue	A tongue based interaction medium requires the tongue to be moved left or right or bitten between the teeth. E.g. a tongue activated switch.	Feasibility Trial 1	5.2
IM: • Voice **UAR**: • Speaking clarity	A voice interaction medium requires the user to speak	Suggestion from Validation Phase 3	9.4.2

Interaction Mediums (IM) / Technology Planning Relationships (TPR)			
IM: • Arm **TPR**: • Head Mounted Display (HMD)	An arm movement requires high agility due to the small buttons on a HMD.	Observations from Evaluation 3	7.4
IM: • Arm **TPR**: • Smartphone • Tablet • Switches	An arm movement requires low agility due to the larger buttons on Smartphones, Tablets and Switches	Observations from Evaluations 1 and 2	7.2 7.3
IM: • Brainwave Detection **TPR**: • EEG	Operating EEG technologies requires high brain agility.	Feasibility Trial 1	5.2
IM: • Chin **TPR**: • Switches	A chin movement requires low agility due to the large size of Switches.	Literature reviews of assistive technologies	2.8

IM: • Eye **TPR**: • Smartphone • Tablet • HMD • Head Tracking • Eye Tracking	The technologies require high visual acuity as the smartphone, Tablet, HMD and Head Tracking rely on viewing displays that are relatively small. Eye Tracking requires good control of the eyes.	Feasibility Trial 4 and 5 and observations from Evaluations 1, 2 and 3	5.5 5.6 7.2 7.3 7.4
IM: • Eye **TPR**: • EEG • Switches	Low visual acuity is required as EEG can detect brain signals or eye movements regardless of vision. Switches are large and can be operated with reduced or no vision.	Observations from Feasibility Trial 1	5.2
IM: • Fingers **TPR**: • Smartphone • HMD	High finger agility (dexterity) is required to operate the touch screens on smartphones and small buttons on HMD.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4
IM: • Fingers **TPR**: • Tablet • Switches	Low finger agility (dexterity) is required to operate Tablets due to the increased screen size and Switches as they are large and easy to press.	Literature reviews of assistive technologies	2.8
IM: • Foot **TPR**: • Switches	Low foot agility is required to operate Switches as they are large and easy to press.	Literature reviews of assistive technologies	2.8

IM: • Hand **TPR**: • Smartphone • HMD	High hand agility is required to operate the touch screens on smartphones and small buttons on HMD.	Observations from Evaluations 1, 2 and 3 Literature reviews of assistive technologies.	7.2 7.3 7.4
IM: • Hand **TPR**: • Tablet • Switches	Low hand agility is required to operate Tablets due to the increased screen size and Switches as they are large and easy to press.	Literature reviews of assistive technologies.	2.8
IM: • Head **TPR**: • Head Tracking	High head agility is required to operate Head Tracking as it relies on 80° neck movement left or right.	Observations from Evaluation 2	7.3
IM: • Head **TPR**: • Switches	Low head agility is required to operate Switches as they are large and easy to press.	Literature reviews of assistive technologies	2.8
IM: • Suck and Blow **TPR**: • Smartphone • Tablet • Switches	High agility is required to operate sucking and blowing devices.	Literature reviews of assistive technologies	2.8

IM: • Tongue **TPR**: • EEG • Switches	High agility is required to move the tongue left, right or bite between the teeth.	Feasibility Trial 1	5.2
IM: • Voice **TPR**: • Smartphone • Tablet • HMD	Speech is required as voice control relies on the user being able to speak, regardless of the device.	Suggestion from Validation Phase 3	9.4.2

Physical Conditions (PC) / User Abilities Relationships (UAR)			
PC: • Brain Injury • Cerebral Palsy • Motor Neuron Disease • Muscular Dystrophy • Multiple Sclerosis • Parkinson's • Stroke **UAR**: • Ey • M • V • S • EL • W • H • A	These physical conditions have the potential to affect all user abilities to varying extents.	Literature reviews of physical conditions Suggestions from Validation Phase 3	2.2.1 9.4.2

PC: • Brittle Bone Disease • Polio • Spina Bifida • Spinal Cord Injury **UAR**: • M • V • S • EL • W • H	These Physical Conditions have the potential to affect all user abilities except eye movements, which are not a contraindication.	Literature reviews of physical conditions Suggestions from Validation Phase 3	2.2.1 9.4.2
PC: • Osteoarthritis • Scoliosis **UAR**: • S • EL • W • H	These Physical Conditions have the potential to affect all user abilities except eye and mouth movements including voice, which are not contraindications.	Literature reviews of physical conditions	2.2.1 9.4.2

User Abilities Correlations (UAC)			
UAC: • Sucking • Blowing	There is a strong positive relationship between sucking and blowing as both abilities are required for example to operate a Sip 'n' Puff technology.	Literature reviews of assistive technologies	2.8
UAC: • Lifting shoulder • Bending elbows • Moving wrists	There is a strong positive relationship between lifting the shoulder, and bending the elbow, as the joints operate in parallel when operating technology, e.g. HMD. Similarly, to operate a smartphone requires the bending of elbows and movement of wrists.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4
UAC: • Moving wrists • Bending thumbs • Bending fingers	There is a positive relationship between moving the wrists, and bending thumbs and fingers, as these movements may correspond but it is possible to move the wrists independently of thumbs and fingers when operating technology and vice-versa.	Observations from Evaluations 1, 2 and 3	7.2 7.3 7.4

Appendix P: SmartAbility Validation Questionnaire

Name: ____

Email/phone:____

Domain background: ____

Number of years' experience:____________________________________

1. Can you please comment on the relationships between User Abilities and Interaction Mediums, i.e. do the mappings make sense to you?

2. Can you please comment on the relationships between User Abilities and Physical Conditions, i.e. do the mappings make sense to you?

3. Can you please comment on the relationships between Technology Planning and Interaction Mediums, i.e. do the mappings make sense to you?

4. Can you please comment on the correlations between User Abilities shown in the roof of the model, i.e. do the mappings make sense to you?

5. Can you please comment on the Target Ranges, i.e. are they an accurate indication of User Ability?

6. Can you please comment on the ‘ease of understanding’ the QFD model, i.e. does it make sense to you?

7. Can you please comment on the model key, i.e. is it self-explanatory?

8. Can you please comment on the Data Dictionary terminology, i.e. does it sufficiently explain the aspects of the QFD?

9. Do you think that the SmartAbility Framework would be useful to the disabled user community?

No		Not sure		Yes
1	2	3	4	5

10. Do you think that the SmartAbility Framework would be useful to the healthcare domain?

No		Not sure		Yes
1	2	3	4	5

11. Do you think that the SmartAbility Framework would be useful to the technology domain?

No		Not sure		Yes
1	2	3	4	5

12. Using your domain knowledge, please provide examples of where the SmartAbility Framework could be used.

For further information, please contact:
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Thank you for your time

SmartAbility Validation Phase 3 Feedback

t (14 years' experience as consultant, 30 years as a medical doctor)

	Rationale	Action
	Physical Conditions	
e element	Conditions can be selected in a number of ways, i.e. common types, congenital or acquired, childhood and adult.	Conditions to be split into acquired and congenital categories.
tions is not	The resulting impairments from conditions vary depending on their severity.	No action following consideration.
physical terms of and muscle	The categories provide an indication of the type of condition.	No action following consideration.
could be bility or	The definition of the term is not clear.	Rename as 'Associated Components'.
	Abilities	
wn, left, right	The action of looking implies that the neck needs to move whereas gaze implies movement of the eyes only.	No action following consideration.
e rephrased as and tilting the	It is not possible to move the neck without moving the head.	Rename as 'Head Movements'.

Comments	Rationale	Action
Abilities could be grouped in to broad categories to assist readability, i.e. head and neck, upper limbs, lower limbs, speech and vision.	Having a long list of abilities is difficult to read and should be separated into smaller sections.	Include the categories of 'Head and Senses', 'Upper Limbs' and 'Lower Limbs'.
From a medical viewpoint, wrist movements are considered from the supine position, i.e. palms facing up, but the framework is referring to movements from the prone position, i.e. palm facing down.	This needs to be defined as movements are considered differently depending on the viewpoint.	No action following consideration.
The ability to see should be referred to as Visual Acuity. The measurement of 20:20 in terms of vision is now outdated (Imperial) and should be referred to as 6:6 (Metric).	Seeing is known as Visual Acuity in the medical domain.	No action following consideration.
Target ranges are generally too great for the purposes of the framework, e.g. a 90˚ shoulder movement is not required for arm interaction.	Subtle types of movement (e.g. 10˚-20˚) are required for interaction, as coarse movements of >45˚ are rarely required for interaction with technology.	Use target ranges of >20˚ for all movements with the exception of turning the head that requires 80˚.
Voice Interaction does not require 100% speech clarity.	Interaction could be made through a noise, grunt, yes/no sound and not necessarily speech.	Modify 'Speech Clarity' to 'Ability to Speak' as a Boolean statement.
Shoulder Movements should be referred to as Abduction of Shoulder.	Shoulder movements should be referred to as Abduction of Shoulder in the medical domain.	No action following consideration.
Interaction Mediums		
Voice interaction can be in different languages	English is not the only language used for voice interaction.	No action following consideration.
Technologies		
Muscle movement sensors could be incorporated into the element.	Muscle movement sensors are a form of technology that is not considered by the framework.	Consider for future development.

Comments	Rationale	Action
House of Quality		
The purpose of the roof of the model is not so clear.	The mappings shown in the roof are not obvious to users without explanation.	No action following consideration.
Data Dictionary		
Definition of the relationship between brain interaction and EEG could be improved to 'EEG requires electrodes that can detect brainwave impulses'.	This is a more accurate definition than the existing term.	Update definition.
The relationship between hand interaction and tablet technology should include that user interfaces on tablets can have larger buttons than smartphone interfaces.	This is a difference between smartphones and tablets that is not considered in the data dictionary.	Update definition.
The relationship between head interaction and head tracking technology should include head movements rather than neck movements to reflect the change to the Abilities element.	To be consistent with Abilities element.	Update definition.

General Feedback
The HoQ is very useful for precisely detailing the framework mappings and structure. It is very useful to have clear definitions stated in the Data Dictionary. The framework will be very useful to the disabled user community. Useful to the technology and healthcare domains, specifically: • Rehabilitation medicine. • Children/paediatrics. • Orthotics/mobility devices • To create a comprehensive assessment in children and young adults or older patients who have disabilities head injuries. • Spinal injuries patients such as Stoke Manderville and Odstock Hospitals.

Participant 2

Lecturer in Adult Nursing (many years' experience of nursing)

Comments	Rationale	Action
Physical Conditions		
Questioned whether the element is required.	It seems that the framework is limited to the physical conditions mentioned when it is actually applicable to all physical conditions.	No action following consideration.
Abilities		
Questioned the use of the term 'biting tongue'.	This phrase is ambiguous as it could mean biting something between teeth or just biting.	Rename as 'Biting tongue between teeth'.
Up and down tongue movements are not considered.	It is noticeable that only left and right tongue movements are included in the element.	Consider for future development.
Voice clarity could be rephrased as a Boolean statement, 'ability to speak'.	Voice interaction does not require 100% speech intelligibility and therefore a Boolean statement is more representative.	Modify 'Speech Clarity' to 'Ability to Speak' as a Boolean statement.
To improve the usability of the element, options could be included to state whether the user has full or no function of each group of abilities.	This will save the user time in completing the element rather than selecting each ability individually.	Consider for future development.
Without testing, the target ranges appear an accurate indication of abilities.	The ranges are understandable.	Use target ranges of >20˚ for all movements with the exception of turning the head that requires 80˚.

General Feedback
The mappings of user ability to physical conditions makes sense but are generalised and do not consider severity of condition. However, this is not an issue, as the framework allows for individual differences through the user abilities. The HoQ is easy to understand and based on explanation and domain knowledge, the roof is clear. The Data Dictionary is easy to understand. The SmartAbility Framework is significantly clearer than in the first validation. The terminology used is now similar for a person without domain knowledge to understand. The framework is more user-friendly and very useful for the disabled user community, technology and healthcare domains, specifically through: • Raising health professional awareness (including students) of the different types of technologies available to support people with disabilities. • Speech therapists/occupational therapists/physiotherapists to guide people to the app for assessment if they are not currently using technologies. • Individuals with temporary disabilities (e.g. accidents) for assistance during the rehabilitation phase.

Participant 3

Lecturer in Software Engineering, 12 years' experience of software engineering

Comments	Rationale	Action
Abilities		
There is no consideration of combinations of movements, i.e. moving the arm with or without the shoulder.	Movements often involve two or more aspects of the body.	State an assumption that only single movements are considered by the framework.
Interaction Mediums		
It is not currently possible to interact with technology solely with the brain.	Is it only possible to interact with the brain using a brain wave detector as the technology is not advanced enough. Using the term 'Brain' as an interaction medium implies that interaction can be performed only with the brain and without any supporting technology.	Rename as 'Brainwave Detection'.
It is not clear whether foot interaction utilises use of foot or the ankle.	There are different ways to interact using the foot and the framework needs to explicitly state how foot interaction is performed.	State an assumption that foot interaction should not include the ankle.
There are two possible types of interaction mediums, input and output.	The framework should state whether it is focussing on input or output interaction mediums.	State an assumption that the framework only considers input interaction mediums.
Technologies		
The element does not state the interaction method in the technology name.	There should be multiple columns for each technology, e.g. 'Smartphone by touch', 'tablet by joystick'.	No action following consideration.
The term 'switch' needs to be defined.	It is not clear what is meant by 'switch', as there are many different types of switch and the size is important.	Define 'Switch' in the Data Dictionary.

Comments	Rationale	Action
'Movement Agility' is not applicable to all technologies, e.g. the brain.	The term should be renamed 'Agility' as this does not specifically refer to movement and can be applied to all technologies.	Rename as 'Agility'.
Data Dictionary		
The Data Dictionary will require updating to reflect the above changes.	To maintain consistency.	Update Data Dictionary accordingly.
General Feedback		
• The framework needs to be consolidated through careful consideration of definitions and assumptions. • The framework will be very useful to the disabled user community, healthcare and technology domains, specifically creating software and systems for a wide range of user abilities.		

Participant 4

Lecturer in Adult Nursing (15 years' experience of nursing and as a chiropractor)

Comments	Rationale	Action
Physical Conditions		
There can be a wide range of ability within one physical condition, e.g. strokes have varying levels of recovery.	The physical condition is less important than the individuals' ability to perform tasks independently or to determine their required support.	No action following consideration.
The actual ability to perform tasks is more important than target ranges of joint movement.	The target ranges are less important than the individuals' ability to perform tasks independently or to determine their required support.	No action following consideration.
The literature available on range of movement tends to be outdated and does not include accuracy and repeatability of measurement.	This needs to be considered when reviewing literature.	Consider for future literature reviews.

Abilities		
From a chiropractic viewpoint, the importance is placed on the users' ability to perform tasks rather than their range of movement.	Even though some people may have restricted range of movements, it may not adversely affect their ability to perform tasks. For example, despite the users' fingers not bending 20°, it may not restrict them from dressing independently.	No action following consideration.
Interaction Mediums		
High Agility arm and hand-based interactions are not essential for smartphone use.	It is possible to operate a smartphone with low arm and hand agility.	Amend mapping between smartphone and arm/hand-based interactions to 'Low Agility'.
General Feedback		
The HoQ is understandable, however, orientation was needed before model was understood. The supporting text helped understanding. The Data Dictionary was thorough. The SmartAbility framework will be very useful to the disabled user community, technology and healthcare domains specifically in rehabilitation following a stroke. The framework would be an ideal tool for guiding individuals to possible technology solutions to suit their disability.		

Participant 5

Principle Academic in Games Technology (17 years' experience of artificial intelligence, virtual reality and Human Computer Interaction)

Comments	Rationale	Action
Physical Conditions		
The element is clear and detailed but there may be a need to investigate combinations of abilities.	This may lead to alternative interaction mediums being selected for users.	Consider for future development.
Abilities		
There may be a need to define the relationship between Macro movements (e.g. shoulder) and micro movements (e.g. fingers).	To assist with classification of the user abilities.	No action following consideration.
Target Ranges must ensure that fluctuations of ranges over the performance of the interactions need to be considered.	The user may become tired or their condition evolves, leading to an adverse effect on ability.	Consider for future development.
Interaction Mediums		
May need to consider technologies that incorporate more than one input type.	The need to include a wider selection of new technologies is essential for software development.	Consider for future development.
House of Quality		
The symbols could be more standardised to improve the usability of the SmartAbility application.	This would adhere to principles of learnability of mobile user interfaces.	Consider for future development.

General Feedback
Believe the mappings between abilities and physical conditions provides enough detail to cater for a wide range of physical conditions. The HoQ clearly shows a correlation between different abilities. The key is clear and meaningful. The data dictionary terminology is detailed enough but may require refining once the framework had been exploited. The framework will be very useful to the disabled user community and healthcare domain and useful to the technology domain, specifically: • To enhance the development of computer games by offering equivalent input technologies to suit users with reduced physical abilities. • Allow software developers to not limit the development to tailor specific input software.

Participant 6

Occupational Therapist (20+ years' experience occupational therapy)

Comments	Rationale	Action
Physical Conditions		
Spinal Cord Injury is acquired.	It is not a congenital condition.	Reclassify Spinal Cord Injuries as a congenital condition.
Include Motor Neuron Disease as an acquired condition.	This is another common physical condition.	Include Motor Neuron Disease and perform literature review.
Neck, shoulder, elbow, finger and ankle conditions are not included for Multiple Sclerosis, Motor Neuron Disease, Parkinson's disease and Spinal Cord Injury.	These are contraindications of the conditions.	Include the relationships.
Speech impairment is not included for Acquired Brain Injury, Multiple Sclerosis, Parkinson's disease and Spinal Cord Injury.	This is the contraindication of the conditions.	Include the relationships.
Abilities		
Define the meaning of 'Easy', 'Difficult' and 'Impossible'.	These are ambiguous without definition.	Include the definitions in the Data Dictionary.
Need to include stability in the trunk as an ability.	Stability enables arms to move freely away from the body in order to use hands functionally.	No action following consideration.
Could include fixing/stabilising the elbow or shoulder to enable hand function.	Users may only be able to interact with technology if their body is supported.	State assumption that the abilities need to be performed without external support.

General Feedback
The relationship between Abilities and Interaction Mediums are reflected by the framework. Target Ranges appear to be accurate. HoQ is easy to understand and key is self-explanatory. The examples in the Data Dictionary assist with the terminology. The SmartAbility Framework will be very useful to the disabled user community, technology and health care domains, specifically; • An internet based application to be offered to Disabled Living Centres to assist, advise and inform their client • Technology suppliers to advertise their products. • Allied Health Professionals (Occupational Therapists, Physiotherapists and Speech and Language Therapists) and General Practitioners to increase awareness of technology. • Could be promoted at the Rehab Week in London (June 2017), The OT Show, or NAIDEX Exhibition. Ask Sara by the Disabled Living Foundation is an example of a recommendation system for home equipment.

Appendix R: Consolidated SmartAbility Elements

Physical Conditions Element

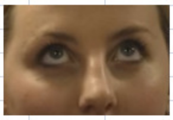
	Physical Conditions (i)											
	Acquired								Congenital			
Associated Components	Brain Injury	Multiple Sclerosis	Motor Neuron Disease	Muscular Dystrophy	Osteo-arthritis	Parkinson's Disease	Polio-myelitis	Spinal Cord Injury	Brittle Bone Disease	Cerebral Palsy	Spina Bifida	Stroke
Joints												
Partial neck movement	✓ (blue)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (blue)		✓ (red)
Partial shoulder movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (red)	✓ (red)		✓ (red)
Partial elbow movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (red)	✓ (red)		✓ (red)
Partial wrist movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (red)		✓ (red)
Partial finger dexterity	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (blue)		✓ (red)
Partial ankle movement	✓ (red)	✓ (green)	✓ (green)		✓ (red)	✓ (green)	✓ (purple)	✓ (green)	✓ (black)	✓ (red)		✓ (red)
Joint hypermobility									✓ (red)			
Joint dislocation									✓ (red)			
Scoliosis										✓ (blue)		
Muscles												
Contractures	✓ (red)	✓ (red)		✓ (red)			✓ (purple)			✓ (red)		✓ (red)
Dyskenesia		✓ (red)				✓ (red)				✓ (red)		
Atrophy		✓ (red)	✓ (green)	✓ (red)	✓ (red)		✓ (purple)	✓ (red)			✓ (red)	✓ (red)
Paraplegia	✓ (black)	✓ (red)		✓ (red)	✓ (red)		✓ (purple)	✓ (red)		✓ (blue)	✓ (red)	✓ (red)
Quadraplegia / tetraplegia	✓ (red)	✓ (red)					✓ (purple)	✓ (red)		✓ (red)		
Hemiparesis	✓ (black)						✓ (purple)			✓ (blue)		✓ (red)
Vision												
Visual	✓ (red)	✓ (red)								✓ (blue)		✓ (red)
Cataracts				✓ (red)								
Sensory												
Dizziness										✓ (blue)		
Speech	✓ (green)	✓ (green)	✓ (green)	✓ (red)		✓ (black)				✓ (blue)		

Reference Key

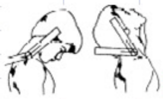
✓ (red)	Andrews,R., 2014. Disabling conditions and ICF measures [Microsoft Excel]. Cambridge: Addenbrooke's Hospital. Unpublished.
✓ (purple)	Healthline Networks Inc, 2015. *Polio: Types, Causes and Symptoms* [online]. San Francisco: Healthline Networks Inc. Available from: http://www.healthline.com/health/poliomyelitis [Accessed 9 December 2015].
✓ (black)	Whittington, P., Dogan, H. and Phalp, K. (2015) SmartPowerchair: to boldly go where a powerchair has not gone before. Ergonomics & Human Factors 2015, Daventry, UK, 13-16 April 2015. 233-240. CRC Press, London, UK.
✓ (blue)	Experimentation observations
✓ (green)	Validation suggestions

Abilities Element

[1]


[2]


Physical Abilities (vii)(x)	Target Ranges	Ease of Action		
		Easy	Difficult	Impossible
HEAD AND SENSES				
Head [3](ii)				
Tilting head upwards	>20°			
Tiliting head downwards	>20°			
Turning head left	80°			
Turning head right	80°			
Eye [2]				
Gazing upwards	Y/N			
Gazing downwards	Y/N			
Gazing left	Y/N			
Gazing right	Y/N			
Blinking	Y/N			
Seeing	6:6			
Mouth [4]				
Sucking	Y/N			
Blowing	Y/N			
Biting tongue between teeth	Y/N			
Moving tongue left	Y/N			
Moving tongue right	Y/N			
Smiling	Y/N			
Voice [1](v)				
Speaking	Y/N			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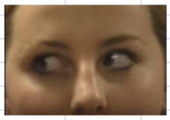
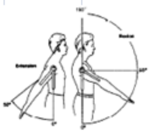
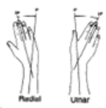

[2]

Abilities Element (cont.)



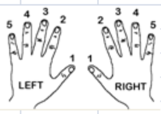
[1]

[1]



[1]

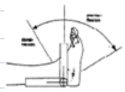
[1]



[5]

[1]

UPPER LIMBS				
Shoulder [3]				
Lifting left shoulder	>20°			
Lifting right shoulder	>20°			
Elbow [3]				
Bending left elbow	>20°			
Bending right elbow	>20°			
Wrist [3](iii)				
Moving left wrist inwards	>20°			
Moving right wrist inwards	>20°			
Moving left wrist outwards	>20°			
Moving right wrist outwards	>20°			
Moving left wrist downwards	>20°			
Moving right wrist downwards	>20°			
Moving left wrist upwards	>20°			
Moving right wrist upwards	>20°			
Hand [3]				
Bending left thumb	>20°			
Bending right thumb	>20°			
Bending second left finger	>20°			
Bending second right finger	>20°			
Bending third left finger	>20°			
Bending third right finger	>20°			
Bending fourth left finger	>20°			
Bending fourth right finger	>20°			
Bending fifth left finger	>20°			
Bending fifth right finger	>20°			
LOWER LIMBS				
Ankle [3]				
Bending left ankle downwards	>20°			
Bending right ankle downwards	>20°			



[1]

Abilities Element (cont.)

References

[1]	Bowen, C., 2015. *The proportion of a speaker's output that a listener can readily understand* [online]. Wentworth Falls, NSW: speeech-language-therapy dot com. Available from: http://www.speech-language-therapy.com/index.php?option=com_content&view=article&id=29:admin&catid=11:admin&Itemid=117 [Accessed 27 February 2016].
[2]	entukvideo, 2009. *Ocular Range of Motion and Ocular Alignment* [video, online]. Available from: https://www.youtube.com/watch?v=tQT0f1AVNmAb [Accessed 27 February 2016].
[3]	Washington State Department of Social and Health Services, 2013. *Range of Joint Motion Evaluation Chart* [online]. Tacoma, WA: Washington State Department of Social and Health Services. Available from: https://www.dshs.wa.gov/sites/default/files/FSA/forms/pdf/13-585a.pdf [Accessed 27 February 2016]
[4]	Whittington, P., Dogan, H. and Phalp, K. (2015a) Evaluating the Usability of an Automated Transport and Retrieval System. The 5th International Conference on Pervasive and Embedded Computing and Communication Systems, Angers, France, 11-13 February 2015. 59-66. Science and Technology Press, Lisbon, Portugal.
[5]	ideallaedi, 2012. Archive for 'piano-promenades' category [Online]. Available from: https://ideallaedi.wordpress.com/category/piano-promenades/ [Accessed 27 February 2016]

Interaction Mediums Element

Ability:

● Mandatory

○ Non-mandatory

Physical Abilities	Interaction Mediums (ix)										
	Arm [10]	Brainwave Dectection [8]	Chin [4]	Eye [2]	Fingers [4]	Foot [4][viii]	Hand [1]	Head [3]	Sip n Puff [4]	Tongue [10]	Voice [6]
Head [3]											
Tilting head upwards	○	○	●	○	○	○	○	●	○	○	○
Tilting head downwards	○	○	●	○	○	○	○	●	○	○	○
Turning head left	○	○	●	○	○	○	○	●	○	○	○
Turning head right	○	○	●	○	○	○	○	●	○	○	○
Eye [2]											
Looking upwards	○	●	○	●	○	○	○	○	○	○	○
Looking downwards	○	●	○	●	○	○	○	○	○	○	○
Looking left	○	●	○	●	○	○	○	○	○	○	○
Looking right	○	●	○	●	○	○	○	○	○	○	○
Blinking	○	●	○	●	○	○	○	○	○	○	○
Seeing	●	○	○	●	●	○	●	●	●	○	○

Interaction Mediums Element (cont.)

Mouth [4]											
Sucking	○	○	○	○	○	○	○	○	●	○	○
Blowing	○	○	○	○	○	○	○	○	○	○	○
Biting tongue between teeth	○	●	○	○	○	○	○	○	○	●	○
Moving tongue left	○	●	○	○	○	○	○	○	○	●	○
Moving tongue right	○	●	○	○	○	○	○	○	○	●	○
Smiling	○	●	○	○	○	○	○	○	○	○	○
Voice [1]											
Speaking	○	●	○	○	○	○	○	○	○	○	●
Shoulder [3]											
Lifting left shoulder	●	○	○	○	○	○	○	○	○	○	○
Lifting right shoulder	●	○	○	○	○	○	○	○	○	○	○
Elbow [3]											
Bending left elbow	●	○	○	○	○	○	○	○	○	○	○
Bending right elbow	●	○	○	○	○	○	○	○	○	○	○

Interaction Mediums Element (cont.)

Wrist [3]											
Moving left wrist inwards	●	○	○	○	●	○	●	○	○	○	○
Moving right wrist inwards	●	○	○	○	●	○	●	○	○	○	○
Moving left wrist outwards	●	○	○	○	●	○	●	○	○	○	○
Moving right wrist outwards	●	○	○	○	●	○	●	○	○	○	○
Moving left wrist downwards	●	○	○	○	●	○	●	○	○	○	○
Moving right wrist downwards	●	○	○	○	●	○	●	○	○	○	○
Moving left wrist upwards	●	○	○	○	●	○	●	○	○	○	○
Moving right wrist upwards	●	○	○	○	●	○	●	○	○	○	○
Hand [3]											
Bending left thumb	●	○	○	○	●	○	○	○	○	○	○
Bending right thumb	●	○	○	○	●	○	○	○	○	○	○
Bending second left finger	●	○	○	○	●	○	○	○	○	○	○
Bending second right finger	●	○	○	○	●	○	○	○	○	○	○
Bending third left finger	●	○	○	○	●	○	○	○	○	○	○
Bending third right finger	●	○	○	○	●	○	○	○	○	○	○
Bending fourth left finger	●	○	○	○	●	○	○	○	○	○	○
Bending fourth right finger	●	○	○	○	●	○	○	○	○	○	○
Bending fifth left finger	●	○	○	○	●	○	○	○	○	○	○
Bending fifth right finger	●	○	○	○	●	○	○	○	○	○	○

Interaction Mediums Element (cont.)

Ankle [3]											
Bending left ankle downwards	○	○	○	○	○	●	○	○	○	○	○
Bending right ankle downwards	○	○	○	○	○	●	○	○	○	○	○
	[1]	[9]	[6]	[3]	[6]	[6]	[2]	[4]	[6]	[7]	[8]

Interaction Mediums Element (cont.)

References

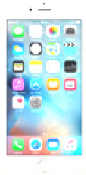
[1]	Assistive Technology, 2016. *Switches and Input Devices* [Online]. Leeds: Assistive Technology. Available from: http://assistive-technology.co.uk/products/switches_and_input_devices
[2]	AV Lounge, 2015. Logitech Harmony Smart Control [Online]. Harrow: AV Lounge. Available from: http://www.avlounge.co.uk/logitech-harmony-smart-
[3]	Fixational Ltd., 2015. *Fixational - Eye gesture control for apps - wink camera, eye tracking*. Galway: Fixational Ltd. Available from: http://www.fixational.com/
[4]	Komodo OpenLab Inc., 2014. iPhone and iPad accessibility options for quadriplegics and other users with limited mobility. *Tecla by*
[5]	Jokisch, M., Bartoschek, T. and Schwering, A., 2011. Usability testing of the interaction of novices with a multi-touch table in semi public space [Online]. *In HCI International 2011*, Orlando, FL 9-14 July 2011. New York, NY:
[6]	Permobil Europe BV., 2015. *MagicDrive EC: Problems are there to be solved* [online]. Brighouse: Permobil Europe BV. Available from: http://www.permobil.com/en-GB/English/Other-products/Electronics/Magic-Drive-EC/ [Accessed 23 December 2015].
[7]	Synder, T., 2013. *New Wheelchair Technology Allows for Tongue-Controlled Commands*. Savage,MN: Rollx Vans. Available from: http://www.rollxvans.com/new-wheelchair-technology-allows-tongue-controlled-commands/ [Accessed 29 July 2016].
[8]	Rushing, K., 2015. *Voice Control in the Home* [Online]. New York, NY: Scripps Networks LLC. Available from: http://www.hgtv.com/remodel/mechanical-systems/voice-control-in-the-home [Accessed 23 December 2015].
[9]	United News Network GmbH., 2010. *Official patent approval for the "actiCAP" EEG cap approaches* [Online]. Karlsruhe: United News Network GmbH. Available from: http://www.pressebox.com/pressrelease/brain-products/Official-patent-approval-for-the-actiCAP-EEG-cap-approaches/boxid/336978 [Accessed 23 December 2015].

Technologies Element

Interaction Mediums	Technologies						
	Smartphone [1]	Tablet [2]	Head Mounted Display [3]	Eye Tracker [4]	Head Tracker [6]	Electroencephalogram [9]	Switch [10]
Arm	□	□	■				□
Brain Wave Detection						■	
Chin							□
Eye	▲	▲	▲	▲	▲	▲	△
Fingers	■	■	■				□
Foot							□
Hand	□	□	■				□
Head					■		□
Sip n Puff	■	■					■
Tongue						■	■
Voice	◆	◆	◆				

Actions

Using	■	High agility
	□	Low agility
Seeing	▲	High acuity
	△	Low acuity
Speaking	◆	High clarity
	◇	Low clarity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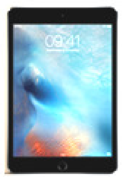
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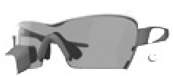
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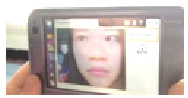
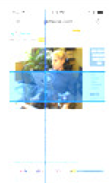
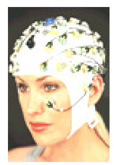

[4]






[9]

Technologies Element (cont.)

References

[1]	Apple Inc, 2016. *iPhone 6s: The only thing that's changed is everything* . [Online]. Cupertino, CA: Apple Inc. Available from: http://www.apple.com/uk/iphone/ [Accessed 06 January 2016].
[2]	Apple Inc, 2016. *iPad mini 4: Mighty. Small.* [Online]. Cupertino, CA: Apple Inc. Available from: http://www.apple.com/uk/ipad-mini-4/ [Accessed 06 January 2016].
[3]	Recon Instruments, 2016. *Recon JET: Smarter eyewear. Built by athletes for athletes.* [Online]. Vancover, BC: Recon Instruments. Available from: http://www.reconinstruments.com/products/jet/ [Accessed 06 January 2016].
[4]	Miluzzo, E., Wang, T. and Cambell, A.T, 2010. EyePhone: activating mobile phones with your eyes [Online]. In: MobiHeld '10 - 2010 ACM SIGCOMM Workshop on Networking, Systems, and Applications on Mobile Handhelds, New Delhi 30 August - 03 September 2010. New York NY: ACM. Available from: http://dl.acm.org/citation.cfm?id=1851328 [Accessed 08 January 2016].
[5]	Despoke, 2010. Eyephone: Operate A Cell Phone With Your Eyes. *Despoke* [Online]. 31 May 2010. Available from: http://www.despoke.com/2010/05/31/eyephone-operate-a-cell-phone-with-your-eyes/ [Accessed 08 January 2016].
[6]	Apple Inc, 2016. *iOS: Switch Control helps you navigate your iOS device* . [Online]. Cupertino, CA: Apple Inc. Available from: https://support.apple.com/en-gb/HT201370 [Accessed 06 January 2016].
[7]	Komodo OpenLab Inc., 2014. iPhone and iPad accessibility options for quadriplegics and other users with limited mobility. *Tecla by Komodo* [Online]. 05 June 2014. Available from: http://gettecla.com/blogs/news/14347593-iphone-and-ipad-accessibility-options-for-quadriplegics-and-other-users-with-limited-mobility [Accessed 11 January 2016].
[8]	Brain Products GmbH, 2016. *actiCAP - The third generation of active electrode* [Online]. Gilching: Brain Products GmbH. Available from: http://www.brainproducts.com/productdetails.php?id=4 [Accessed 06 January 2016].
[9]	Loughran, S.,2015.Alternative ways to control a power wheelchair. *ATandMe* [Online]. 31 July 2015. Available from: http://www.atandme.com/?p=950 [Accessed 06 January 2016].

Table of Assumptions

Assumptions

i	Physical Conditions relate to both adults and children, as the conditions can be congenital or acquired at any point in life.
ii	Head movement involves the neck as well as the head.
iii	Wrist movements are referred to from the prone position, i.e. palms facing downwards.
iv	In order to interact with technology, subtle movements are required i.e. >20°. Course movements of >45° are not required for interaction.
v	Voice interaction does not require 100% speech clarity, as different forms of vocalisation can be used such as a grunt.
vi	If the Ease of Action of an ability is impossible, it is implied that the user does not possess that ability.
vii	The framework only considers single movements and not combinations of movement.
viii	Foot interaction does not include the ankle.
ix	The framework only considers input Interaction Mediums.
x	The user needs to be able to perform the abilities without external support.