iMOCO4.E

Intelligent Motion Control under Industry 4.E

D2.1 State-of-the-art methods in Digital Twinning for motion-driven high-tech applications

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Abstract:

Quote from the Description of Action (Annex 1 Part A):

"This deliverable presents a market scan (also among consortium partners) and literature survey on the state of the art in digital twinning solutions and the application of AI. Digital twinning and AI will be considered at several levels, ranging from module-level to production-line-level. The report will also describe emerging technologies in this field and identify development directions for IMOCO4.E."

This document first addresses the reference architecture of a typical IMOCO4.E system (described from different viewpoints), and then considers the 10 Building Blocks that are defined in the IMOCO4.E project outline.

This deliverable D2.1 provides essential input to the succeeding documents D2.2, D2.3 and D2.4 of WP2.

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Abbreviations

Abbreviation	Explanation
AI	Artificial Intelligence
ANN	Artificial Neural Network
AR	Augmented Reality
ASSP	Application Specific Standard Parts
BB	Building Block
CASB	Cloud Access Security Broker
CNC	Centralized Network Configuration
CNC	Computer Numerical Control
COTS	Commercially Of The Shelf
CPU	Central Processing Unit
DoA	Description of the Action
DSP	Digital Signal Processor
DT	Digital Twin
EDR	Endpoint Detection and Response
FPGA	Field-Programmable Gate Array
FWaaS	FireWall as a Service
HW	Hardware
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IVRA	Industrial Value chain Reference Architecture
LASFA	LASIM Smart Factory
LASIM	Laboratory for handling, assembly and pneumatics
MBSE	Model Based System Engineering
MCU	MicroController Unit
MQTT	Message Queuing Telemetry Transport
NTA	Network Traffic Analysis
OPC	Open Platform Communication

Abbreviation	Explanation
OPC UA	OPC Unified Architecture
PLC	Programmable Logic Controller
RAMI 4.0	Reference Architectural Model Industry 4.0
RUL	Remaining Useful Life
SASE	Secure Access Service Edge
SIEM	Security Information and Event Management
SINDy	Sparse Identification of Nonlinear Dynamics
SITAM	Stuttgart IT Architecture for Manufacturing
SLAM	Simultaneous Localization and Mapping
SOAR	Security Orchestration, Automation and Response
SoC	System-On-Chip
SoPC	System-On-Programmable-Chip
SotA	State of the Art
SWG	Secure Web Gateway
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
VR	Virtual Reality
WAN	Wide Area Network
WP	Work Package
XDR	Extended Detection and Response
ZTNA	Zero-Trust Network Access

Executive Summary

This document addresses the State-of-the-Art methods that are relevant for the IMOCO4.E reference platform. This reference platform consists of AI and digital twin toolchains and is further based on the 10 smart building blocks that have been described in the DoA. The target applications of this reference platform are novice and complex motion controlled industrial systems.

The State-of-the-Art descriptions cover a broad maturity range, from the academic research trends (low TRL) to commercially available products (high TRL). These descriptions can give proper direction to the IMOCO4.E development activities, aiming that European knowledge is brought from the academia to the industry, and that the European industry is strengthened in its market proposition.

Thus, in this document, a market scan is presented of current COTS solutions, and the most promising emerging trends are identified. The identified shortcomings of and the potential IMOCO4.E progress beyond the State-of-the-Art are the starting points for the next document deliverables, of which D2.2 elaborates on the needs for future smart production in Europe. Thereafter, D2.3 refines the outcome of D2.1 and D2.2 into overall requirements on the IMOCO4.E reference framework.

1. Introduction

1.1 Purpose of the Document

The objective of WP2 is to specify the common, generic and architectural requirements for setting up a typical IMOCO4.E system. WP2 also aims to give direction to the plans and actions for the anticipated developments in the IMOCO4.E project, to be executed by the consortium partners.

The first task of WP2 is Task2.2, which results in this D2.1 deliverable document. This document describes the starting position (i.e. the current state-of-the-art) for the IMOCO4.E developments, covering a broad TRL-range from academic research work to commercially of the shelf (COTS) solutions on the market. D2.1 also addresses the presently known shortcomings of, and potential/suggested progress beyond the current SotA. Basically, this is a refinement of the IMOCO4.E ambitions described in the description of the action (DoA).

The output of D2.1 serves as the input of D2.2, which dives deeper into the needs for future smart production.

Furthermore, the outputs of D2.1 and D2.2 together serve as the input of D2.3 and D2.4, which dive deeper into the IMOCO4.E reference framework requirements and specifications.

The focus of WP2, hence also of D2.1, is on high-tech motion-driven applications and systems, with specific emphasis on the role of digital twinning and data-driven (learning) AI-technologies.

1.2 Structure of the Document

Chapter 2 describes the state-of-the-art reference architecture. It does so from three different viewpoints:

The **structural viewpoint** concerns the reference architecture and framework of a typical IMOCO4.E system. Since this topic will be elaborated in more detail in D2.3 and D2.4, this section is intentionally kept briefly for now, to avoid duplicate information across D2.1 and these documents.

The **functional viewpoint** concerns the digital twinning solutions. Since digital twinning is a rather broad concept, this chapter is specifically tailored to the field of motion control systems. The viewpoint on the application of AI is deliberately omitted in this chapter because this topic is also addressed in various BBs in chapter 3.

The **toolchain viewpoint** concerns the various Model Based System Engineering (MBSE) tools and the interoperability between these tools, during the development and entire product life cycle.

Chapter 3 describes the state-of-the-art per BB, so at module-level, of a typical IMOCO4.E system. There are 10 Building Blocks defined in the IMOCO4.E project outline, so this chapter contains 10 respective subchapters.

1.3 Intended readership

This document has public dissemination, meaning that - while it is intended for all IMOCO4.E partners - it will be made available also outside the IMOCO4.E consortium.

The readers of this document are intended to use it as a book of reference for all resulting activities, including but not restricted to the entire IMOCO4.E project.

2. State-of-the-Art Reference Architecture

2.1 Structural viewpoint

This chapter starts with a few definitions:

- An **architecture** is a structure, style, abstract idea, data flow, interoperability, methodology, concept or design pattern of a system.
- A **framework** is something which implements the style, idea, concept etc. of an architecture, or makes it easier to implement it.

Any system can be built according to a chosen architecture, where the implementation is possibly realized by means of a suitable framework.

The boundary of such a system can be taken into consideration. Comparing a typical IMOCO4.E system with a typical I-MECH system yields:

- I-MECH System = Anything that moves or controls
- IMOCO4.E System = IMECH System + cloud/data + digital twin + cybersecurity + operational infrastructure

While the I-MECH project focused on the core of motion control (i.e. mainly on layers 1 and 2, including interfaces to layer 3, but less on layer 3 itself), the IMOCO4.E project takes much more of the entire end-to-end solution into account.

The I-MECH and IMOCO4.E projects both include also the (model-based) development tools and simulations in their scopes.

2.1.1 Reference architectures

Industry 4.0 (also called the Industrial Internet of Things (IIoT)) has already led to a few reference architectures for industrial manufacturing systems. The six most well-known reference architectures have been compared [14], and their gaps, shortcomings and challenges have been identified.

These architectures are: RAMI 4.0, IIRA, SITAM, IVRA, IBM Industry 4.0 and LASFA. As can be seen in Figure 1 below, the differences between these architectures become evident when the mapping to the Industrial Automation Pyramid is made.

It is relevant to mention that the I-MECH reference architecture [1] maps only to the lower half of the pyramid. Taking the objectives of IMOCO4.E into consideration, it is logical that the IMOCO4.E reference architecture shall include a mapping to the operation level, with potentially a relation to the enterprise (business) level as well. This will be elaborated further in deliverables D2.3 and D2.4 of the IMOCO4.E project.

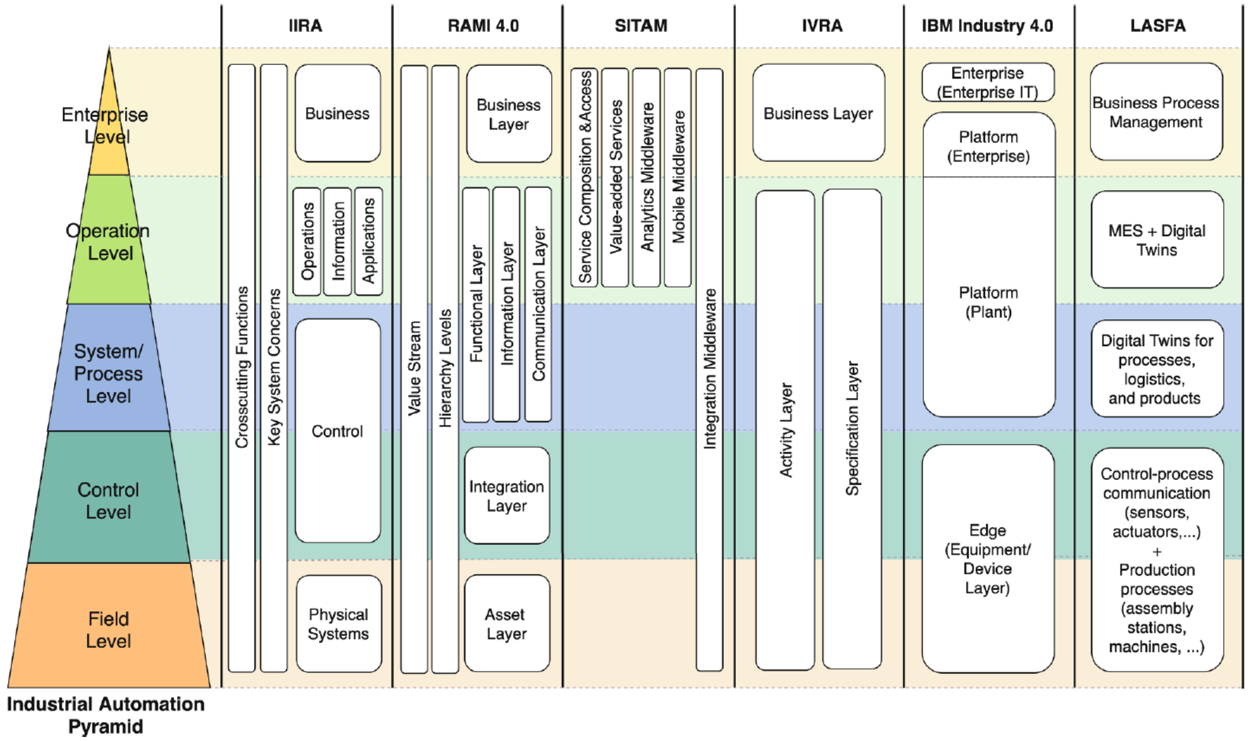

Figure 1 Mapping of Industry 4.0 reference architectures to the industrial automation pyramid

2.1.2 Identified benefits and shortcomings

In the above-mentioned comparison [14], the following main shortcomings have been identified:

- There is a lack of consensual standardization on architectural elements, and consequently an almost self-evident lack of framework technology with assured quality to build an implementation.
- Interoperability is still a big challenge. How the data and communication flows are established between various components at various system levels is poorly detailed, leading to unnecessary hurdles and limitations in industry projects.
- Reference architectures should also encompass legacy (sub)systems, while assuring end-to-end qualities. Moreover, such legacy (sub)systems often need to continue operating. There is no real consensus how to deal with these situations efficiently.
- Reference architectures should also combine different technologies that make the components (machines, devices, PLC, robots, software systems like ERP and digital twins, and others). This mindset is not established in a broader sense.

While addressing these shortcomings above is yet a challenge on its own, an additional need of an overall architecture is to assure all categories of end-to-end qualities, like security, trust, privacy, sustainability, compatibility, interoperability, serviceability, etcetera, etcetera.

2.2 Functional viewpoint

For the functional viewpoint on the reference architecture, Digital Twinning and AI will be considered in this document at several levels, ranging from module-level to production-line-level. The lower levels are described in chapter 3 (break down by BBs), while the system level is described here below.

2.2.1 Digital Twins

2.2.1.1 Market scan, COTS solutions (high TRL)

When looking at the current market, many domain or client-specific digital twin implementations can be found, such as the following examples:

- Philips HeartModel: Digital twin of human heart.
- IBM Port of Rotterdam, Container 42: Shipping box full of sensors.
- Siemens Electrical Digital Twin: Digital twin for power grids.
- Siemens Digital Twin for Red Bull F1 car.

However, it is noted that only a few frameworks and general solutions are found:

- Prespective: Visualization, connection to real machine or simulator, building blocks for simulation, based on Unity3D.
- Masters of Pie: NX plugin, VR/AR/HoloLens, collaboration in virtual room.
- Dassault 3DEXPERIENCE: cloud platform linking different tools, whole lifecycle, different disciplines.

It seems that the current solutions have mainly the visualization aspects in mind (on-screen/VR/AR/MR), supported by simulators of the system and its environment (including human interactions). However, the DT being an exact and maintained digital copy of its real-world counterpart (including instance configuration and corresponding datasets) is still less common.

2.2.1.2 Emerging trends (rising TRL)

Metaverse: meant to be next iteration of the internet, consisting of 3D environments and interactive avatars. It is centred on solving current limitations of VR/AR devices and expanding these worlds to involve business and education (while entertainment is already a large player in online interaction in 3D environments).

2.2.1.3 Literature & academic research (low TRL)

The analysis of the literature on digital twins takes the advantage of the availability of many literature reviews and surveys realized in recent years on this topic. The concept of digital twin was proposed by Michael Grieves during his course at the university of Michigan in 2002. The title of his one slide was „Conceptual Ideal for PLM“, where PLM stends for Product Lifecycle Management. Proposed figure already had all the elements of digital twin – real space, virtual space, the link for data flow from virtual space to real space and virtual sub-spaces [4].

Many authors say that the first digital twin approach was used by NASA during Apollo 13 mission which is not very much the truth. The twins used in this happening were physical twins of the aircraft and even though they played an important role, they were not digital counterparts in the sense of digital twins as we know them today [6].

Since the first introduction of the digital twin notion, there has been many definitions provided. The backbone of these definitions is common and can be represented by three important components:

- a model of the object,
- an evolving set of data relating to the object, and
- a means of dynamically updating or adjusting the model in accordance with the data.

Based on the system type for which the Digital twin is designed and used, digital twins can be subdivided into following four groups [2]:

- **Component twins** – digital representations of an individual part of a system or product.
- **Asset twins** (product twins) – digital representation of physical product, often composed from several component twins.
- **System twins** (unit twins) – combination of products working together, comprises how assets interact with each other.
- **Process twins** – representation of systems working together, model of a manufacturing line or entire factory.

Recently, several papers [11][13] appeared trying to give the precise definition of what the digital twin is and what it is not. These rigorous definitions concentrated more on precise definition, trying to prevent the overlap with other existing technologies and approaches, rather than to define it as a helpful **technology supporting the product during all its lifetime, i.e., from its initial ideas to its end of life**. Some researchers stuck on the precise interpretation of the word twin being replica of something existing which naturally results in the explanation that before we can have a digital twin, the real system must already exist. This explanation is very restrictive since it excludes the usage of digital twins until first prototype is produced or even to first sample production. This situation is commented on by the spirit father of the Digital Twin [5] by calling it the "Digital Twin Exists ONLY After There Is A Physical Product" fallacy. Indeed, the model-based design is very helpful, it is utilized very often and significantly contributes to rapid prototyping and therefore it makes sense to include it under the umbrella of digital twin.

A special model is the key component of a digital twin. Wright [13] makes the distinction between ordinary model and a special one which create the basis of the digital twin. Tao [11] illustrates the digital twin modeling from the six modeling aspects:

1. **Model construction** – geometric (shape, size, internal structure, spatial position, and attitude), physical (static, dynamic, multi-physics, finite elements), behavioral (sequential, concurrent, linked, periodic, and random behaviors of physical entities) and rule (mining and analysis of whole life cycle data)
2. **Model assembly** – model lightweight while keeping model accuracy and functionality, interference problems detection to make successful assembly
3. **Model fusion** – between model dimensions, between models in different fields
4. **Model verification** – information reconfirmation (model is refined until satisfactory), vertical analysis (verification of historical parameters), concept and fidelity analysis, logic tracing
5. **Model modification** – selection of adequate number of parameters, selection of reasonable methodology for modification
6. **Model management** – multidimensional and multi-field model management, authority management, selection of technology and management tools

For each modeling aspect, the paper summarizes available technologies and tools based on the analysis of over 300 cited papers.

As complex machines and robots have become increasingly connected throughout the Industry 4.0 era, large potential in data and analytics is created. However, essential knowledge of the system cannot always be described using sensorial data, because of constraints in the environment or due to the lack of space. Therefore, the physical system modelled through an exact digital replica, the Digital Twin. A Digital Twin aims to replicate a physical system's structure, behavior, and environment through sensorial data, physical or data-driven models of the physical asset, and environmental knowledge. As such, a Digital Twin can generate modelled data through *soft sensors*, provide feedback, detect physical issues sooner, and optimize the manufacturing process [10].

Digital Twin technologies can be applied on several levels of granularity in precision. For each level, the description and modeling of the physical asset becomes increasingly detailed. The commonly known granularity levels consist of *components*, *systems*, and *aggregations*, also known as systems-of-systems [7] [10]. Within the IMOCO4.E project, a rolling bearing could represent a component, a 3D printer could represent a system, and a fleet of 3D printers could represent an aggregation. For each Digital Twin, the objective and complexity of the model varies. A component Digital Twin may be used to offer predictive maintenance insights, the system digital twin may gather customer preferences for the marketing and sales teams, and gather information to optimize product performance and efficiency, while the aggregate Digital Twin may feed operational data into production and planning models for strategic insights and roadmaps [8].

In practice, the objective to achieve using the Digital Twin leads to different architectural designs. Tekinerdogan [12] developed a catalog for Digital Twin design patterns. In this catalog, they identified nine design patterns: Digital Model, Digital Generator, Digital Shadow, Digital Matching, Digital Proxy, Digital Restoration, Digital Monitor, Digital Control, Digital Autonomy. For each of the design patterns, they provide its lifecycle stage, context, problem description, solution, structure, and dynamics. The design patterns were categorized using the ISO/IEC 15288 System Lifecycle stage standard: Concept, Development, Production, Utilization and Support, and Retirement stages.

Semeraro [7] also identified that the following companies have developed support for Digital Twins, or even ship Digital Twin platforms: GE Predix Platform, SIEMENS PLM, Microsoft Azure, IBM Watson, PTC Thing Worx, Aveva, SAP Leonardo Platform, Twin Thread, DNV-GL, Dassault 3D Experience, Sight Machine, and Oracle Cloud.

Augmented and Virtual Reality are a key technology in Cyber-Physical systems to integrate human interaction into the loop. In the design stage, AR and VR can assist developers and customers to see a configuration from anywhere. This reduces the need of travel, and may increase the success rate of later operations, as the asset could be evaluated inside the environment digitally. Siemens also identified virtual factory acceptance testing, virtual commissions, and remote monitoring of the asset as key benefits from employing AR and VR technology [3].

2.2.1.4 Partner solutions (any TRL)

SIOUX has developed a generic framework (called SuperModels + Holodeck) to help with a large part of a digital twin creation. This includes the system structure (based on CAD models) and high-level behaviour (both controller and simulator) to enable an on-screen and/or VR system. This framework is mainly employed during the prototype phase of a project but can remain valuable during the later phases of the product life cycle. Recently, elementary sensor feedback has been added to the virtual environment, so that the controller is now able to respond interactively on a much broader set of events.

2.2.1.5 Identified shortcomings

Because the known frameworks have a rather generic character, they do provide little or no domain and client specific solutions. Which means that still a lot of “tailoring” and “customization” is needed for most systems.

One particular topic is the modelling of the "products" that are handled by a system. In other words, even if the modelling of the structure and behaviour of a system may be in place, there is also the need for adequate modelling of the material flow that goes through the system (and undergoes some manipulations).

Furthermore, none of the frameworks is "feature-complete" so that it assists in every aspect of a digital twin development. To be more precise on these aspects: a digital twin is intended to support different use cases during a system life cycle, like:

- System development (on virtual hardware)
- System service (fault analysis) and training
- System condition monitoring and trend predictions
- System optimization; factory optimization

Again, the current frameworks already have focus on the visualization aspects of the digital twins, and the main shortcomings are more in the area of data collection and analysis: To support the use cases with simulation, co-execution, play-back (&compare), and evaluation of different "what-if" scenarios.

2.2.1.6 Potential IMOCO4.E progress beyond SotA

The goal of IMOCO4.E it to set down an architecture, that leads to new or improved framework(s) assisting in most aspects of a digital twin.

The current (baseline) frameworks can already generate code for controllers and simulators, and visualize the systems, on screen or in VR or AR. The following progress could be potentially made in IMOCO4.E:

- It can support collaboration and interaction of people around the world in a virtual room.
- It can help during the many phases of a project's lifecycle.
- It can play back data logged from a real machine at a later point in time.
- Related to AI and data analytics, it can be used to generate data before a real machine is available, or for bad weather scenarios at any point in time.
- A telemetry solution can be introduced where data from a real machine is collected and made available for visualization, and for (off-line or on-line) processing by AI algorithms.

2.2.1.7 Applicable standards, methods, tools

Within Microsoft Azure, digital twins are described by a Digital Twin Definition Language (DTDL) [15].

2.2.2 AI and Data-Driven Learning Techniques

Since the components for AI and Data-Driven Learning Techniques are allocated to BB8, the detailed State-of-the-Art description is therefore addressed in chapter 3.8 and intentionally not duplicated here.

The functional aspects of a suitable reference architecture to enable AI and data-driven techniques is for the rest mainly concerning data acquisition, communication and storage (in a cyber-secure way), which is allocated to BB9 and therefore addressed in chapter 3.9. This covers both acquisition of learning data and deployment of trained neural networks.

2.3 Toolchain viewpoint

This section describes the current state of the art in Model Based System Engineering (MBSE) tools and toolchain interoperability. This is an important topic for IMOCO4.E because the scope of an IMOCO4.E system (see section 2.1) will become rather large, and consequently the number of tools for developing and maintaining such a complete system will increase accordingly. In order to assure the consistency between all system components during the development and entire product life cycle, it is getting more and more important that the product information is continuously exchanged and synchronized between the used tools.

2.3.1 Market scan, COTS solutions (high TRL)

Several commercial solutions exist on the market today, the most applicable and prominent listed below.

Intercax

Intercax describes Syndeia as 'a software platform for integrated model-based engineering'. It creates what is described as a 'digital thread'. The underlying technology is based on OSLC. It provides integrations for several engineering tools that provide:

- A reference connection, to jump to related items and check if an items has changed.
- A model transform connection: allowing items in different domains to be synchronized.

Syndeia uses an architecture with tool plugins on use machines connected to a cloud infrastructure. Data transfer is done using APIs and file transfer.

SBEvision

SBEVision provides an 'integration platform for Next-Gen interoperability and Digital Engineering', that uses a combination of OSLC based linking and publish subscribe based synchronization methods to provide interoperability in the systems engineering tooling platform [16]. The adapters to connect tools to the platform are either service based (for web-based tooling) or plugin-based for rich client and desktop programs.

Obeo

Polarsys Capella is an Eclipse based MBSE toolkit that supports the Arcadia method. Obeo [17] has a number of products to facilitate interoperability of Capella with OSLC-compliant ALM and RM tools, and Siemens Teamcenter, NX etc. [18].

Siemens, Dassault Systèmes

Siemens, Dassault Systèmes have a range of MBSE tools that provide interoperability with other tools of their ecosystem and a number of third-party integrations:

Siemens has integrations for requirements management, product lifecycle management, change management, etc. [19].

Dassault Systèmes Cameo-Interop [20] allows MagicDraw and 3rd party tools to communicate with Cameo Systems Modeler, based on a.o. XMI.

Ansys, MathWorks

Ansys and MathWorks offer a MBSE ecosystem that provides internal interoperability, with limited options to integrate with third-party tooling.

Modelica

Modelica is an MBSE environment maintained by the non-profit Modelica Association [21]. It provides a standard library for modelling different system aspects and implements several interoperability standards (see the section about standards below).

2.3.2 Emerging trends (rising TRL)

Koneksys

Koneksys provides services to integrate SysML tooling like MagicDraw, Papyrus with Modelica and lifecycle tooling through OSLC.

Itemis

Itemis Yakindu is a collection of tools for requirements management, risk analysis and state modelling with interoperabilty to Enterprise Architect, Matlab Simulink.

Eclipse Lyo

Eclipse Lyo is an open-source implementation of OSLC that can be used as a platform for interoperability of lifecycle management tooling. A sample implementation of SysML exists [22].

2.3.3 Literature & academic research (low TRL)

Several OSLC adapters exist, such as for MathWorks Simulink [23].

OASIS published the results of a survey about integration maturity [24]. The model based approached is used for generation of such integration, see e.g. this Lyo code generator [25].

For Capella a SysML Bridge was researched for MBSE interoperability [26].

Within the BUMBLE project [27] model interoperability is researched aiming at collaborative modelling in different modelling environments.

2.3.4 Partner solutions (any TRL)

Within SIOUX there is a heterogenous systems engineering environment. Several generic tools from different vendors are used for the common aspects of product creation and lifecycle management. These tools are supplemented with a couple of privately developed workbenches and platforms that address specific needs and benefits of the SIOUX organization and the SIOUX projects. They allow for instance graphical programming and put the mechatronic domain experts in control. Some of them were developed within the I-MECH project [28], a predecessor of IMOCO4.E.

Although these platforms provide no tool integration with external tools, within the BUMBLE project [27] using Jetbrains MPS, a domain specific language (DSL) workbench, was researched to support collaborative modelling within the two environments.

2.3.5 Identified shortcomings

Existing MBSE ecosystems provide more internal integrations than external tool integrations. While OSLC is on the rise as a mechanism to link tooling together, actual interoperability is limited. Within Sioux no tool integration exists at all.

2.3.6 Potential IMOCO4.E progress beyond SotA

To address the previously mentioned shortcomings we intend to create a proof-of-concept implementation to link the existing SuperModels modelling environment to one or more tools used in the product creation. Candidates for this are requirements tools, system architecture tools (SysML) and lifecycle management tooling. During the concept phase of system development, a functional overview of a system is created. This model links the high-level functions (requirements) to the high-level decomposition. The intention is to create a specific language in SuperModels and link it externally defined requirements and system decomposition.

2.3.7 Applicable standards, methods, tools

The INCOSE Tools Integration & Model Lifecycle Management working group (TIMLM WG) created an overview of existing standards and the roadmap, itself to be described by IEC 24641 [29]. In it the following standards are described that are applicable to this theme:

- STEP – product data exchange specification by the PDES consortium
- SysML – Systems Modelling Language by object management group, a general-purpose architecture modelling language for systems engineering application.
- OSLC – Open Services for Lifecycle Collaboration, specifications to allow independent software and product lifecycle tools to integrate their data and workflows in support of end-to-end lifecycle processes.
- LOTAR NAS9300-520 - focuses on data preservation, reuse, accident investigations, maintenance, regulations, obsolescence, safety. Application versions 3y, storage/access 10yrs, stage formats for 50yr product cycles.
- ReQIF – Requirements Interchange Format developed by the Object Management Group: XML based format to exchange requirements with associated metadata.
- Modelica FMI Functional Mock-up Interface [30] standard to define container and interface to exchange dynamic models using a combination of XML files, binaries and code in a single file.
- Modelica System Structure and Parameterization (SSP) – to define and parameterize a system out of one or more functional mock-ups that can be transferred between simulation tools.
- Modelica Distributed Co-Simulation protocol (DCP) – communication standard for integration of models or real-time systems into simulation environment

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3. Module & Component SotA (BB decomposition)

3.1 BB1 SoC/FPGA platforms

This building block will rely on heterogenous FPGA and ARM-based industrial AI-edge embedded computing platforms – as opposed to standard computer platforms – to incorporate high-performance computing close to the deep edge of the system. In line with the Industry 4.0 vision, standard and open methodologies will be applied at different layers to orchestrate the different elements, while preserving the determinism and reliability of the control system. The direct interface with the physical signals will yield into latency and performance to power ratio improvements.

3.1.1 Market scan, COTS solutions (high TRL)

All ARM based heterogeneous embedded platforms featuring GPU, DSP, NPU, TPU and FPGA – FPGA resources can be very relevant for some application specific hardware acceleration development. Some of the well know SoCs available in today are: iMX8 and iMX8M series from NXP [1][2], the NVIDIA Carmel and Volta from NVDIA [3], the MPSoC Ultrascale+ and the Versal AI Edge devices family from Xilinx [4], the Intel Cyclone V family from Intel [5] or the TDA4VM from Texas instruments [6] to name a few.

Intel Cyclone V family comprises several FPGA and SoC FPGA platforms. The later ones include an Arm-based Hard Processor System (HPS). Intel Switch and switched TSN [7] endpoints are among the solutions provided by the Intel Cyclone SoC FPGA.

Xilinx also offers FPGA and Arm-based MPSoC FPGA platforms on the 7-Series and Ultrascale+ families. MPSoC FPGAs consist of both FPGA programmable logic and a hardware processing system on the same die. On one hand, Zynq-7000 7-Series platforms [8] are based on dual-core 32-bits ARMv9. On the other hand, Zynq Ultrascale+ are based on a powerful dual or quad-core ARM-A53 processor as well as the dual processor R5F for hard real-time tasks. Top platforms also include an ARM Mali 400MP2 GPU core.

Like Intel, Xilinx as well as third-party vendors offer TSN switching and endpoint IP-cores suitable for Zynq-7000 and Ultrascale+ platforms. Those include the required timing system as well as the firmware interfacing with the different modules.

Both FPGA vendors offer development platforms enabling fast prototyping and evaluation. Some examples are the *Aries Embedded PolarFire SoC FPGA module* or *PolarFire Soc Icicle Kit*, from Altera [9]. Xilinx provides ZCs 702 and 706 for Zynq-7000 as well as the ZCUs 102 and 106 for Zynq Ultrascale+. Software suites are available for both HDL design, synthesis and simulation. Some examples are Simulink HDL coder [10], Questa [11], and in the particular case of Xilinx, Vivado and Vitis [12][13].

Furthermore, there are commercial solutions supporting TSN features from different vendors. Some of them are specially focused to 5G applications Falcon RX from FibroLan [14], 7050SX-64 from Arista [15]. Schneider Electric is leading the introduction of TSN on the Smart Grid, TTech as well as multiple vendors have TSN technologies applied to the automotive sector [16][17]. In the particular case of Industrial Automation, it is worth to mention Hirschmann or National Instruments controllers supporting TSN features [18].

3.1.2 Emerging trends (rising TRL)

Some of the observed emerging trends today are the integration of AI capable SoCs in connected devices (AI powered technology at the edge) for IIoT and cyber-physical systems [19]. Leveraging AI technologies for fast time to market product development and preventive maintenance as well as the deep learning for vision systems.

This new paradigm requires network infrastructure adaptability supporting the flexibility and resiliency required for these distributed instances. Besides, the network infrastructure should deliver the bandwidth required for the heavy monitoring data transmission, and support the coordination between the distributed nodes, by providing delivery guarantee for the control messages and time synchronization to give a common time knowledge to every network instance. However, the major challenge is to service the flexible and powerful computation delivered by the AI distributed instances and the and, at the same time, the hard real-time, reliability and interoperability demanded by the sensors and devices already deployed on the factory plant.

Whereas the Time Sensitive Network enhancements can provide the required convergence and interoperability on the Ethernet L2, the introduction of Software Defined Networking paradigms can deliver the flexibility and manageability for the configuration of the mixed critical data stream routing and scheduling driving the TSN. On top of that, SDN delivers the abstraction required to orchestrate the network behaviour with the current application requirements and already-deployed communications infrastructures [20].

Currently, there are some standardization initiatives (IEEE 802.1Qcc, IEEE 802.1Qdj) within the 802.1 TSN working group to define the vendor-neutral interfaces required to abstract the different features of the TSN and expose them to network user applications and the orchestration through a Centralized Network Configuration (CNC) [21][22].

These standardization efforts are clearly aligned to those carried by the OPC foundation defining the OPC Unified Architecture (OPC UA) or by OASIS with the MQTT Sparkplug among others to provide a vendor-neutral and homogenous framework to manage the heterogeneous devices present in the plant, as well as flexible capability to host new technologies on the different layers. The TSN provides the deterministic QoS and reliability on the switching layer.

3.1.3 Partner solutions (any TRL)

TSN core (Orolia)

Within this framework, Orolia has developed a TSN IP core oriented to moderated-cost space avionics [23][24]. This application required low resource usage while supporting mixed-critical data flows including the mission-critical ones and ultra-reliability. This IP core delivers IEEE 802.1Q VLAN tagging and bridging, Time-aware traffic shaping as well as Frame Replication and Elimination for Reliability over 1000-Base-T, 1000-Base-X or 10G-Base-R [25][26].

CLIQ Bricks (Sioux)

The current solution within Sioux is called “CLIQ Bricks”, which is essentially the resulting BB1 output from the I-MECH project.

3.1.4 Identified shortcomings

The main shortcomings are the operationalization and deployment (inference) of AI powered technologies on embedded devices. Mainly because embedded devices have a different set of requirements and their generally limited available computational resources and diversified architectures requires tailored solutions, which usually lack an integrated toolchain.

The integration of the already deployed sensors and fieldbuses into the time sensitive network will be another topic to be covered.

3.1.5 Potential IMOCO4.E progress beyond SotA

3.1.5.1 General

Developing technologies will deliver edge processing and interoperable platforms for industrial automation devices. The resulting control system will integrate different equipment, such sensors, actuators, HMIs or robots, through wireless (WiFi, tG) or wired Ethernet media, such EtherNET/IP, PROFINET or EtherCAT [27][28][29]. Time Sensitive Network (TSN) can be used for smooth integration and evolution of industrial standards, as it enables open, real-time deterministic communications, suitable for the Industrial Automation devices. The *CLIQ Bricks* solution would be extended with developments addressing the topics of Digital Twins, AI and tool integration.

3.1.5.2 Related to Digital Twin

By definition, digital twins are virtual copies of entire systems (or even aggregation of systems). The granularity and level of detail of such a DT instance may or may not extend to the layer in which BB1 exists. In other words, a BB1 can be either "invisible", a black box or a white box in the DT. A potential progress in IMOCO4.E would be that a (full or partial) digital copy of BB1 exists in the DT.

3.1.5.3 Related to AI and Data analytics

Artificial Intelligence powered technologies have found their way into practically all kinds of applications and products. To improve their QoS, there is a need to collect (via almost all smart devices or application software we can thing of today) and analyse huge amount of data, originating from the edge. Decentralizing data architecture is becoming more and more relevant as it improves security and reduce latency. This paradigm shift calls for new technology perspective and workflows.

3.1.6 Applicable standards, methods, tools

This will depend on the business case and the markets segments of interest. From the point of view of vision systems and cyber-physical systems, it could be relevant to think about high-speed bus interfaces and wireless connectivity as well as the contingency of risks associated with connected equipment – including security aspects. With respect to TSN, the technologies are specified on several IEEE 802.1Q enhancements, based on the VLAN differentiation and prioritization of the data streams. Some of them are the Time-aware traffic Shaper introduced in the IEEE 802.1Qbv amendment, as well as the frame pre-emption capabilities IEEE 802.1Qbu. The Frame Replication and Elimination for Reliability protocol defined on the IEEE 802.1cb specification provides zero-time link recovery for safety-critical data streams. The generalized Precision Time Protocol, defined on the IEEE 802.1AS is the basis of the stringent coordination required between the different elements on the edge network. The frame pre-emption capability is ultimately supported by interspersing express traffic (IEEE 802.3br) feature on the Medium Access Control layer.

Nevertheless, several standardization initiatives and recommendations have arisen in recent years to incorporate Software Defined Networking capabilities to Time Sensitive Networks. These can be found on IEEE 802.1Qcc, IEEE 802.1Qci, LLDP, DetNet (RFC8655 and FRC9023), OPC-UA.

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3.2 BB2 High speed Vision in the Loop

Building Block 2 will fuse requirements from High Performance Computing (HPC) and high speed camera data acquisition on a Real Time deterministic computing platform. Applications will include co-located closed loop feedback control and will implement algorithms from classic control as well as various machine learning algorithms.

3.2.1 Market scan, COTS solutions (high TRL)

There are no known Commercial-off-the-Shelf (COST) offerings combining the functionalities of HPC, massive IO and RT µsec deterministic timing for machine vision.

3.2.2 Emerging trends (rising TRL)

Competition between the mayor computing design houses has increased significantly over the last three years. Intel-x86-64 is no longer the only offering. In fact, as of November 2020, the most powerful supercomputer in the world runs on custom-built ARM-based processors [3][4]. Apple recently made a similar decision, replacing Intel chips with its own (ARM) M1 chips. These custom-built ARM-based processors actually surpass the performance of Intel's latest Tiger Lake CPUs for laptops. GPU’s have a tremendous architectural advantage for accelerating machine vision and machine learning applications for they combine thousands of processing nodes with unified memory pools. For years, Intel's Xeon CPUs have dominated the data centre market. However, NVIDIA has also become a critical player in this space, since its graphics processing units (GPUs) are much better at accelerating heavy workloads like artificial intelligence. In fact, NVIDIA's recently launched Ampere GPU is up to 237 times faster than Intel's CPUs. And lastly in recent years, AMD's Ryzen CPU’s have helped the company take significant market share [5]. Machine learning and machine vision are both benefitting from these trends, but integration to the third requirement: real time determinism is missing out.

3.2.3 Literature & academic research (low TRL)

Efforts have been made to utilize GPU’s in vision in the loop, such as by Kato and Rath [1]. This development did however not succeed beyond its thesis. As investigated by Yang, research has been limited since then until 2020 [2]. Luetke [6] researched into the possibility of developing customized device drivers for GPGPU in 2021.

With the recent advancements in the computer vision algorithms, vision has shown a lot of potential as an alternative to traditional sensors for high-speed closed loop control systems. Broadly the computer vision algorithms can be classified into two categories i.e., classical/mathematical image processing approaches [10][11] and machine learning based approaches [8][9][12][13][14]. The classical computer vision algorithms are less compute heavy and requires low memory. Machine learning based algorithms on the other hand can learn very complex patterns and can perform very well in real world scenarios as long as they are trained on good quality datasets.

3.2.4 Partner solutions (any TRL)

A vast literature research dealing with motion control strategies was provided in deliverable D4.1 of IMECH project. Next, to avoid overlapping, a brief state of the art of recent research activities leading with specific control techniques or solutions that are targeted within IMOCO4.E is presented.

3.2.5 Identified shortcomings

Although learning control has increased a lot the last few years, by for instance adding (rational) basis functions, learning control for complex (linear parameter varying, multi-rate, etc.) systems can still be improved. This can be explained since typically black-box methods are used for these complex systems, where the known structure of the system is lost.

Complex programming interface excluding utilisation of tested mainstream software libraries. Although AI and machine vision algorithms have developed greatly during the last decennium, alas the emphasis on time critical and time deterministic requirements has lagged.

State of the art machine learning algorithms [12][13][14] for object detection and image classification are usually compute intensive and thus may have higher inferencing latencies [15], whereas closed-loop control system are more likely to have low latency requirements for a control cycle.

3.2.6 Potential IMOCO4.E progress beyond SotA

The challenge is that vision-in-the-loop requires multiple tasks to be executed simultaneous on one computer. This means that resources and priorities need to be both distributed and managed.

Anticipated developments are the incorporation of High-Performance Computing elements and IO-devices to Real Time deterministic behaviour in a more generic way that is supported by main stream computing libraries.

3.2.6.1 General

To mitigate the shortcomings of these systems in terms of compute resources, energy and memory requirements, a variety of techniques have been explored including but not limited to approximate image processing [16] and platform-aware design flows [9]. The potential IMOCO4.E progress could take these ideas further in the context of high-speed vision in the loop.

3.2.6.2 Related to Digital Twin

Digital Twin technologies require a constant stream of up-to-date information to match the physical and logical state of the process under inspection. This data is generated typically at the edge employing a wide range of sensing components. BB2 will generate input both data via imaging and High-Performance Computing for Digital Twin implementations in the IMOCO4.E project via novel architectures under the most strict time sensitive constraints.

To fine-tune the machine learning models, large amount of application specific dataset is required, digital twins can be crucial in generating artificial datasets in cases where generating good quality dataset from the real-world setup is not a straight forward process. Digital twins can also form a base for HiL and SiL testing platforms of high-speed vision in the loop systems.

3.2.6.3 Related to AI and Data analytics

BB2 will optimize high speed vision architectures and AI/DT algorithms for the deployment on embedded “edge” devices (Embedded GPUs, FPGAs, MPUs, ASICs), with applications in perception, localization, planning, maintenance. This building block will be deployable as a smart sensor for higher control layers.

As mentioned in previous sections, the performance and accuracy of machine learning based models are dependent on the amount and quality of the data used for fine-tuning. Application specific data collection requires additional hardware in place, and to maintain the quality a lot of post processing is needed. IMOCO4.E proposed an alternative to this process in form of digital twins for data generation and system simulation.

3.2.7 Applicable standards, methods, tools

Developments will adhere to open standards as much as possible like POSIX and based on standard Linux operating systems.

- Matlab/Simulink and Python will be the main development environment. Other environments, like Gazebo as simulation environment, will also be used.

- IEC 61131 programming languages for PLC controllers

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3.3 BB3 Novel sensors

BB3 deals with the development of sensing ecosystems that are typically applied in motion control systems. Since this is still a very broad definition, the scope of BB3 in the IMOCO4.E project is deliberately narrowed down to the following exemplary sensor types:

- Radar
- Overmolded sensor
- Event camera
- Vibration sensor

For each of these four sensor types, the state-of-the-art is described in this chapter (each in separate subparagraphs).

3.3.1 Market scan, COTS solutions (high TRL)

3.3.1.1 Radar

Commercial radar sensors for industrial applications with multiple Tx-/Rx-channels are available and applicable typically at these frequencies:

- Radar sensors at 24 GHz (ISM-Band, 250 MHz bandwidth). Examples (suppliers) for commercial solutions: Banner, InnoSent, NanoRadar, Radarxense, Symeo, …
- Radar sensors at 60 GHz (ISM-Band, up to 7 GHz bandwidth): Acconeer, Ainstein, Symeo, Colorado, Staal Technologies, NocelIC …
- Automotive radar sensors at 76-77 GHz and 77-81 GHz (frequency regulation to be verified for industrial use): Bosch, Continental, Smartmicro, Aptiv, Hella, InnoSent, Metawave, Oculii, Veoneer, …

3.3.1.2 Overmolded sensor

In general there are **several small low-power pressure and temperature sensors** such as Bosch MBP series (https://www.bosch-sensortec.com/products/environmental-sensors/pressure-sensors/) with dimensions such as 2mm x 2.5mm x 0.95mm or ST's MEMS pressure sensors (https://www.st.com/en/mems-and-sensors/pressure-sensors.html). These are not however wireless and the need for electrical bonding and wiring impairs the suitability for being overmolded and incorporated into injected plastic parts (the target of Demo 2).

There are already **commercial solutions using overmolded RFID tags**. By using proprietary injection overmolding two-shot technique (that preserves the electronics from damage by the heat and pressure of molding), Xtreme RFID Inc., has produced one-piece, fully encapsulated RFID tags for asset tracking [7][8]. A PPS resin is used which offers high heat and chemical resistance (protection against fuels, oils, and solvents), as well as high mechanical strength for uses in harsh environments such as oil and gas industries, mining, commercial fishing, municipal solid-waste recovery, and general manufacturing.

3.3.1.3 Event camera

Event-based vision sensors, such as the DVS, inspired in their design by biological vision, record data in very compact form at high temporal resolution, with low latency, and high dynamic range, and these properties make then ideally suited for real-time motion analysis. So far, DVS has been mostly an research in academic settings with limited commercial applications. Current COTS in the market is focused on DVS cameras and further development kits for educational and developing purposes, provided by several vendors, including iniVation, Prophesee., Samsung and CelePixel. The recent literature on these new sensors as well as the recent plans for mass production claimed by companies, such as Samsung and

Prophesee, highlights that there is a big commercial interest in exploiting these novel vision sensors for mobile robotic, augmented and virtual reality (AR/VR), and video game applications. However, because event cameras work in a fundamentally different way from standard cameras, measuring per-pixel brightness changes (called "events") asynchronously rather than measuring "absolute" brightness at constant rate, novel methods are required to process their output and unlock their potential.

3.3.1.4 Vibration sensor

Wireless vibration sensors are nowadays available components for machine condition monitoring on the market, but their performance and parameters are somehow limited. There are many types of wireless sensor nodes which waken up by a trigger signal from the parent system and usually send only raw (instantaneous) data during limited timeframe depending on the capacity of a power source utilized. Some of the devices also allows to send processed data (e.g. frequency spectrum, acceleration/velocity peak or RMS values). Few examples of such devices already available on the market are:

- Ranger Pro from Bentley Nevada [37] (raw data and spectrum)
- WiSER 3X from Erbessd Instruments [38] (raw data)
- Wireless Vibration Sensor from NI [39] (raw data)
- VWV001/002 from ifm electronic [40] (RMS value)
- Echo® Wireless Vibration Sensor from PCB Piezotronics [41] (RMS values)
- XS770A Wireless Vibration Sensor from Yokogawa [42] (peak acceleration/RMS velocity values)
- Airius wireless vibration sensor from SPM Instrument [43] (RMS value, signal parameters)

Most of aforementioned sensors are quite heavy (300 – 500 grams) and are large in dimension. Some of these systems use MEMS sensing elements (usually with lower bandwidth), other devices use classical piezoelectric elements for vibration sensing. Power supply of these devices is usually based on primary (galvanic) cells or accumulators with Lithium technology and communication technology uses IEEE 802.15.4 standards for short-range transmission or LoRaWAN for long distances (several kms).

3.3.2 Emerging trends (rising TRL)

3.3.2.1 Radar

Innovations in industrial radar:

- 4D Imaging radar with high number of transmit (Tx) and receive (Rx) channels
- Gesture recognition (e.g. Google Soli-Chip)
- Ultra-high resolution
- Man-machine interface, human interaction/cooperation
- Security enhancement
- Vital signs detection (pulse, breathing, movements)
- Higher frequency bands e.g. 120 GHz (ISM-Band), example: Odosense, Silicon Radar
- AI algorithms and implementation for complex radar signal (e.g. micro-Doppler evaluation)

3.3.2.2 Overmolded sensor

Parker Hannifin is commercializing products with embedded RFID tag such as elastomeric o-rings for anticounterfeiting purposes [11]. Built-In RFID Tags for Plastic Medical Devices offer advantages such as not being able to be peeled-off from the product, inexistence of fail-prone plugs, optimal tag placement and protection (fully encapsulated, hence scratch-free), among others.

3.3.2.3 Event camera

Because the output is composed of a sequence of asynchronous events rather than actual intensity images, traditional vision algorithms cannot be applied, so that new algorithms that exploit the high temporal resolution and the asynchronous nature of the sensor are the research focus currently.

Currently, a practical obstacle to adoption of event camera technology is the high cost of several thousand dollars per camera, due to non-recurring engineering costs for the silicon design and fabrication and the limited samples available from prototype runs. It is anticipated that this price will drop precipitously once this technology enters mass production.

Since the first practical event camera, there has been a trend mainly to increase resolution, increase readout speed, and add features, such as: gray level output (e.g., as in ATIS and DAVIS), integration with IMU and multi-camera event timestamp synchronization. Only recently has the focus turned more towards the difficult task of reducing pixel size for economical mass production of sensors with large pixel arrays.

3.3.2.4 Vibration sensor

- Leaving from integration of classical bulk piezoelectric sensing elements towards MEMS based devices with lower power consumption, smaller dimensions and less output signal noise (higher dynamic range).
- Integration of wireless connectivity into vibration sensors for simple (raw or RMS) data transmission.
- Decentralization of computing power out of a parent system towards sensor nodes.
- Optimization of battery lifetime using on-demand data transmission (based on trigger).

3.3.3 Literature & academic research (low TRL)

3.3.3.1 Radar

3.3.3.2 Overmolded sensor

The recent trend in plastic production dictated by Industry 4.0 demands is to acquire a great deal of data for manufacturing process control. The most relevant data about the technological process itself come from the mold cavity where the plastic part is formed. Manufacturing process data in the mold cavity can be obtained with the help of sensors. Although many sensors are available nowadays, those appropriate for in-mold measurements have demanding and specific requirements [1].

There has been a large R&D effort in the scientific community (including INL [10]) together with industry towards the sensing of in-mold process parameters. On other hand, several developments have been observed (including patents, [6]) regarding the overmolding of RFID (radiofrequency identification) tags especially for anticounterfeiting and part tracing purposes. We aim to use the developments on these fields and merge knowledge in order to develop smart injected products with overmolded tags with sensing capabilities.

A concept of **wireless pressure sensors for the in-mold cavity** was developed by Kazmer and co-workers [3][5][14] in order to eliminate the expensive installation of wires through the mold to connect the sensor. The design of the wireless self-energized cavity pressure sensor [14] consisted of three components: The energy converter, the threshold modulator and the signal transmitter. The energy converter contains a multi-layer piezoceramic element, which generates an electrical charge proportional to the applied pressure. For the transmission of the obtained electrical voltage signal, they used sampling, quantization and encoding. Ultrasound was used as information carrier, and two attributes of the ultrasound pulses were explored to enable dual-parameter sensing: the number of pulses serves as a direct measure for the magnitude of the pressure, and the carrier frequency of the pulses accounts for the polymer melt temperature.

Kazmer et al. [5] presented the experimental results of the dual-parameter wireless sensor application developed for pressure and temperature measurements when injection molding a 40 mm thick part. The obtained results demonstrated a pressure measurement resolution of 122 kPa and a temperature sensitivity of 4.8 kHz/◦C. The authors compared the pressure and temperature profiles obtained with the dual-parameter sensor they developed and commercial wired sensors [3]. The average error for pressure and temperature sensing was measured as below 4% and 5%, respectively.

On I-MECH project, INL [10] developed a custom pressure sensor which was integrated into an injection tool to monitor the different pressure levels along the process cycle, together with a commercial off-the-shelf accelerometer, coupled at the surface of the tool. Both sensors recorded the events over regular productive cycles, retrieving relevant information for smart predictive maintenance.

Regarding RFID tag overmolding, work has been presented in 2016 [4] aiming at the development of cost-reducing techniques for automated integration of RFID tags into plastic (thermoplastic and duroplastic) mass products, addressing the challenge that lies in the fixing method of the tags in the cavity. The RFID transponder are filigree parts made of thin wires and sensitive semiconductor elements, which easily could be damaged by the high pressures, temperatures and shear stresses during the injection molding process. In this project, different fixing methods were evaluated and the RFID tags were adapted to the conditions during the injection molding process concerning technical, geometrical and mechanical aspects. To be able to integrate the filigree tags also in high viscos thermoplastic materials.

Regarding specifically the **overmolding of wireless sensors**, fewer works have been reported. In [13] in-mold labeling of plastic parts has been pursued using passive Radio Frequency Identification (RFID) transponders with temperature sensor capabilities. A concept is presented and evaluated for using temperature sensor equipped passive RFID tags commercially available for part integrated monitoring and control of the injection molding process. Other works focus on the overmolding of some components: in [2] the overmolded packaging of piezoresistive pressure sensors has been pursued using an ultrathick photoresist sacrificial layer (150 μm photoresist block is placed just on the silicon membrane of the pressure sensor and removed after the molding transfer process) while in [12], a PCB-based antenna is overmolded and posteriorly wired.

3.3.3.3 Event camera

- ISSCC-2006-A 128×128 120dB 30mW Asynchronous Vision Sensor that Responds to Relative Intensity Change
- ISSCC-2017-A 640×480 Dynamic Vision Sensor with a 9μm Pixel and 300Meps Address-Event Representation
- ISSCC-2020-A 1280×720 Back-Illuminated Stacked Temporal Contrast Event-Based Vision Sensor with 4.86μm Pixels, 1.066GEPS Readout, Programmable Event-Rate Controller and Compressive Data-Formatting Pipeline

3.3.3.4 Vibration sensor

- Utilization of energy harvesting approaches for sensor nodes (from piezoelectric elements, light, thermal, etc.) [15][16][17][18][19].
- Advanced signal processing directly on sensor node [20][21][22].
- Single devices or distributed network of wireless vibration sensor nodes [23][24][25][26][27][28][29][30][31][32].

- Novel materials and approaches for MEMS based vibration sensors (e.g. cantilevers with AlN piezoelectric thin film, digital sensors) [33][34].
- Power consumption optimization of a wireless vibration sensor node [35][36].

3.3.4 Partner solutions (any TRL)

3.3.4.1 Radar

IMST starts with the “RoKoRa” radar (a result of a funded research project), which is a 77 GHz radar module with 3 Tx and 4 Rx channels with integrated signal processor board and USB or Ethernet interface (TRL = 5 at beginning of IMOCO4.E). This module will be adapted to fulfil the requirements of Demo 3 and to enable AI implementation and processing with additional signal processor.

3.3.4.2 Overmolded sensor

We will pursue robust passive sensors and use the state-of-the art microfabrication facilities to render them suitable for injection overmolding. We target to attribute sensing capabilities, including temperature and pressure, to injection overmolded tags. We will explore RFID /NFC technology, using polyimide-based substrates (flex-PCB) coupled with silicon dies. Although other materials will also be evaluated, polyimide is a good candidate for overmolded sensors given its harsh environments compatibility (chemical resistance, resistance to high temperatures, flexibility) and the compatibility with microfabrication processes (for sensor and antenna integration) of polyimide integrated interconnects [9] to address bonding challenges between sensor/antenna.

3.3.4.3 Event camera

As far as our knowledge goes, there is currently interest from industry in DVS due to its claimed advantages, yet no solution or application for robotics in public domain has been released.

3.3.4.4 Vibration sensor

BUT is focusing on development of wireless sensor network (WSN) nodes based on an extension of their advanced vibration sensor device containing MEMS accelerometers suitable for vibration sensing and health monitoring in industrial environment including in-situ advanced signal processing for direct evaluation of condition indicators. Main aim is to add suitable energy efficient wireless communication interface for the sensor and to sufficiently adjust a hardware structure of the sensor to optimize energy consumption of the device using smart triggering of vibration signal acquisition while maintaining enough sensitivity and resolution to allow more precise mechanical wear detection and prediction. It is expected to implement preferably Bluetooth Low Energy (BLE) communication standard in the device or utilize any suitable standardized IEEE 802.15.4 communication interface. Additionally, specific power supply design using secondary cell (rechargeable battery) is expected to maintain long lasting operation without recharging/changing the battery. Complementation of the power supply circuitry with wireless power transfer is under consideration (for easy recharging the device during its lifetime).

3.3.5 Identified shortcomings

3.3.5.1 Radar

Radar antennas and frontend are not suitable for Demo 3 (forklift application). A new radar frontend with re-designed antenna is required.

Data interface(s) to be adapted to Demo 3, data formats to be defined with partners, data interfaces and formats capable for obstacle detection, path planning and autonomous navigation in industrial environment

Processor capabilities not usable for AI and neural network algorithms implementation, a new radar backend with AI processing capabilities

3.3.5.2 Overmolded sensor

The main challenges regarding overmolding sensors are the thermal expansion coefficients mismatch between the sensor die material (mostly silicon) and the injected polymer which can cause destructive stress on the sensor structure

3.3.5.3 Event camera

In terms of technology, DVS sensors only responds to moving objects in a visual scene if the sensor is placed still and cannot capture static images; The advantage of output sparsity is lost if the sensor moves; High pixel bandwidth makes it sensitive to frequency components that're not visible to human eyes, like light flickering etc.; power advantage over conventional CMOS image sensor at the expense of coarse signal quantization.

3.3.5.4 Vibration sensor

The main challenge is to provide solution which will convince demo owners or end-users that implementation of additional sensors for machine condition monitoring using vibration sensing is beneficial and would help to avoid unexpected downtimes or serious damages. On technical level, there could be limitations in operational time of the device and need for periodic service/replacement/charging of the sensor node. Also, integration of designed sensor network node into specific application can be an implementation challenge, including dimension and weight of the sensor.

3.3.6 Potential IMOCO4.E progress beyond SotA

3.3.6.1 General

3.3.6.1.1 Radar

Radar sensor development for Demo 3 but also applicable for pilots 4 and 5 (healthcare robotics and mining/tunnelling robotic boom manipulator)

3.3.6.1.2 Overmolded sensors

The goal is to have injected parts with wireless temperature and pressure overmolded sensors. For this we will need to develop techniques to minimize generated stress during the injection and reticulation process, such as coatings with materials that will act as mechanical strain absorber. The bonding between the sensor and the antenna will also be target of study as it can represent a bottleneck on the process yield.

3.3.6.1.3 Event camera

- Real-time network communication (TSN)
- EMI noise suppression
- SoC for algorithms

3.3.6.1.4 Vibration sensor

The goal is to provide solution which will be easily implementable on existing machinery, providing required performance and enough operational time for defined task within specific application. This can be done only thorough possibility of flexible configuration of the operation of the device including smart triggering on vibration events and data processing minimizing amount of data to be transmitted to a parent system while maintaining information about the state of the machine – flexible definition of condition indicators and their direct availability at the sensor node.

3.3.6.2 Related to Digital Twin

3.3.6.2.1 Vibration sensor

Flexible wireless sensor node for vibration monitoring can provide useful initial information for model (digital twin) development and allows to utilize advanced high-level diagnosis based on availability of specific (important) model parameters to estimate its changes during operation.

3.3.6.3 Related to AI and Data analytics

3.3.6.3.1 Radar

- Industrial radar sensor with AI capabilities for radar target classification
- Radar sensor for sensor fusion e.g. with video data

3.3.6.3.2 Vibration sensor

Vibration sensor is a source of "big" data in general due to high sampling rate of the primary vibration time signal, but it is not the main intention to create "big" data by the device. Contrary, there is a strong need to process the data at a source (in the sensor, at-the-edge) and provide only useful information to the parent system not to overload communication interfaces and safe power. In case of enough performance at-the-edge, there is a possibility to directly implement a tiny AI approach there (e.g. simple multilayer perceptron neural network) to compute specific condition indicators or directly classify unwanted mechanical behaviour of a monitored mechanical system.

3.3.7 Applicable standards, methods, tools

3.3.7.1.1 Vibration sensor

- Bluetooth® Low Energy (BLE) standard.
- IEEE 802.15.4 standard of low-rate wireless personal area networks.
- Qi wireless power transfer standard.

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3.4 BB4 Real-Time Smart-Control Platform

The goal of BB4 is to enable multiple different workloads at the edge on a single board while ensuring safety and performance. The use of hypervisors will allow to partition the available computing resources in order to separate the AI models from the smart control algorithms or the vision-in-the-loop, and to enhance the performance guarantee required for the system. In addition to the computation, communication between edge devices and the digital twin will be performed by latency-aware mechanisms, such as TSN or EtherCAT, in order to improve the reliability while guaranteeing the required performance.

In this way, it is necessary to focus on different aspects of a platform suitable for that purpose:

- Data processing capacity
- Communication capabilities
- Partitioning
- Flexibility and programmability

3.4.1 Market scan, COTS solutions (high TRL)

3.4.1.1 HW

CPU products:

- x86-based PC (board)
- ARM-based MCU board

SoC products:

- Xilinx UltraScale+ or Versal
- Huawei Atlas (e.g. 200, 300I, 500); Ascend AI processor

Xilinx UltraScale+ or Versal

In the case of Xilinx UltraScale+ or Versal devices, they are FPGA-SoPC devices, i.e., devices combining in a single die a FPGA (PL-Programmable Logic- part) with a multi-core CPU (PS-Processing System-part). These families integrate the software programmability of an ARM®-based processor with the hardware programmability of an FPGA, enabling key analytics and hardware acceleration while integrating CPU, DSP, ASSP, and mixed signal functionality on a single device.

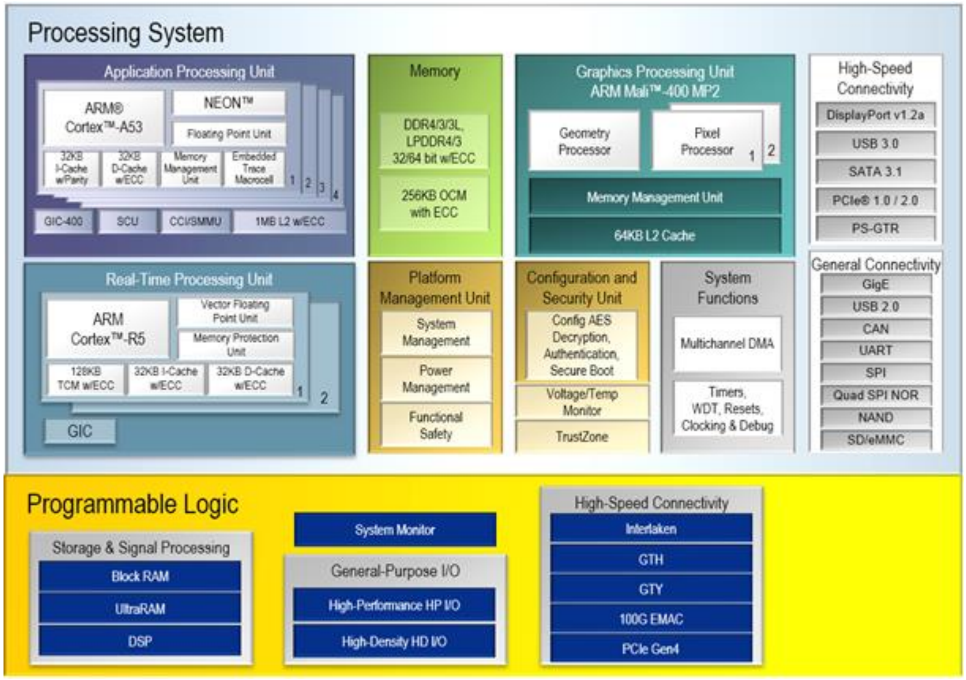

Figure 2 Xilinx Zynq & UltraScale+ Architecture

Data processing capacity. Apart from the ARM multicores, and MALI video co-processor, these FPGA-SoPC systems have an embedded FPGA. This FPGA could be used for accelerating specific data processing operations, among other functionalities.

Versal, the ultimate Xilinx platform, it is considered as the first Adaptive Compute Acceleration Platform (ACAP), as it combines Scalar Engines, Adaptable Engines, and Intelligent Engines to achieve dramatic performance improvements of up to 20X over today's fastest FPGA implementations and over 100X over today's fastest CPU implementations. But Versal is totally out of the scope device for industrial applications.

Communication capabilities. These FPGA-SoPCs have many very powerful means in terms of communication: on one side, its PS part supports natively different communication protocols (serial, ethernet, etc.), on the other side, its PL part, alongside the high-speed embedded transceivers, is capable to accommodate very high speed-rate serial, and Ethernet based, communications.

Flexibility and programmability. What is the greatest advantage that FPGAs have over any other alternative is the fact that they are reprogrammable. This means that even after the circuit has been designed and implemented, FPGAs can still be modified, updated, and completely change its functionality to perform a completely different task than before. Reprogrammability reduces the efforts and cost required for the long-term maintenance of these chips. But additionally, the same HW platform could be used in different use-case and applications, customizing the design inside the FPGA (apart form de SW programmability, of course).

Partitioning. In the FPGA case, a dual partitioning is supported:

- HW-SW partitioning; due to its PS and PL part. The possibility to allow SW offloading to the FPGA part is a great added value in many compute-intensive edge applications.

- SW partitioning; as an ARM based CPU, the FPGA-SoPC system is capable to run a SW hypervisor as well, achieving critical and non-critical functions separation.

FPGA-SoPC systems, are fully compatible with all the frames targeting regular CPUs. But additionally, in the case of Xilinx, it worth to mention Vitis framework. The Vitis™ AI development environment is Xilinx's development platform for AI inference on Xilinx hardware platforms. It consists of optimized IP, tools, libraries, models, and example designs. It is designed with high efficiency and ease-of-use in mind, unleashing the full potential of AI acceleration on Xilinx FPGA. Thus, providing a very comprehensive framework to exploit all the potential of FPGA-SoPC platforms.OS & Middleware:

- VKernel (Virtual Kernel)
- Hypervisor: Jailhouse, Xen hypervisor (Xilinx FPGA-SoPC).
- Real-time OS: NuttX, Zephyr, RTOS32, VxWorks, QNX, RTLinux, Xenomai, Simulink RT, MBED OS, FreeRTOS, ThreadX, SafeRTOS, PIKEOS
- Real-time EtherCAT master

3.4.2 Emerging trends (rising TRL)

The utilization of the real-time BB4 platforms (CPU, MCU, SoC) is growing in the following application fields:

- Data Science
- Explainable AI
- Lean & Augmented Data Learning
- Computer Vision
- Integrated product design
- Change request management
- Multi-dimensional models
- Feedback-loop models
- Machine to machine communication
- Microservices for IAAS
- Multi-Axis Motor Control
- Carrier Ethernet Backhaul

The emerging trend is that the cost of such a system needs to be brought down. By moving away from an off-the-shelf PC to a custom board, not only the cost, but also power usage and space can be reduced. For example, the rising development of 'crossover' MCUs with the ARM Cortex-M7 architecture yields a very promising chip architecture that can support and deliver good general-purpose RTOS capabilities. Supplementary, for certain dedicated and very specific computing tasks, the said SoC products can offer even better performance ratings within the mentioned cost, power and space constraints.

It is a real challenge meeting feature and performance requirements while managing down total project cost. Unlike development costs, considered as NRE costs, system BOM cost typically scales with production quantity. The use of a FPGA-SoPC device carries an extensive cost-optimization, due to all the system is integrated into the same device.

3.4.3 Literature & academic research (low TRL)

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N. Lin, H. Lu, X. Hu, J. Gao, M. Zhang and X. Li, "When Deep Learning Meets the Edge: Auto-Masking Deep Neural Networks for Efficient Machine Learning on Edge Devices," 2019 IEEE 37th International Conference on Computer Design (ICCD), 2019, pp. 506-514, doi: 10.1109/ICCD46524.2019.00076.

P. Mousouliotis et al., "Exploiting Vitis Framework for Accelerating Sobel Algorithm," 2021 10th Mediterranean Conference on Embedded Computing (MECO), 2021, pp. 1-5, doi: 10.1109/MECO52532.2021.9460221.

3.4.4 Partner solutions (any TRL)

Partner solutions of BB4 include various useful architectures to implement multi-dimensional Digital Twin, powered by AI models that are mainly based on unbalanced data sets and optimization algorithms.

Note that BB4 enables (or interfaces with) other BBs in the IMOCO4.E project:

BB1: Possible useful concepts to define better M2M communication.

BB2: Possible useful architectures to implement a multi-dimensional Digital Twin approach (e.g., a virtual model able to consider both the mechanical and the process part of the machinery process and combine them for enabling/improving effective quality checks).

BB8: Useful methods to implement AI models that are mainly based on unbalanced data sets and optimization algorithms.

BB9: Possible useful concepts to define safer M2M communication

For example, partner SIOUX has a mature solution (called SAXCS) that is x86-based and has been demonstrated (as part of Pilot 1) in I-MECH before. Also, within I-MECH, a similar solution has been developed and successfully demonstrated on the NXP iMX.RT1064 processor too. Furthermore, at the lower end, SIOUX also uses STM32F4 MCUs but these are generally too weak for true BB4-related tasks.

Regarding the FGPA-SoPC systems, SoC-e partner has previous experience working with those kind of devices, at HW, SW and RTL level. Additionally, SoCe has in its portfolio a ZYNQ based SoM-System on Module-, and its related development carrier, building up a ‘brick’; but this ‘brick’ is not powerful enough in terms of the populated FPGA (few logic resources in the PL part), as well as in terms of supported interfaces to the outside.

Exertus has developed a portfolio of rugged control system products to meet the tough requirements of heavy machinery sector. The product portfolio is consisting of main controllers, IoT/edge unit, displays, IO-controllers and sensors. The hardware architecture of the products is typically based on multi-core iMX6 and/or Cortex M4/M7 processors equipped with a comprehensive set of peripherals and drivers for e.g., lighting, fans and hydraulic valves. Latest generation controllers are published soon with the top-line processing capacity and other features.

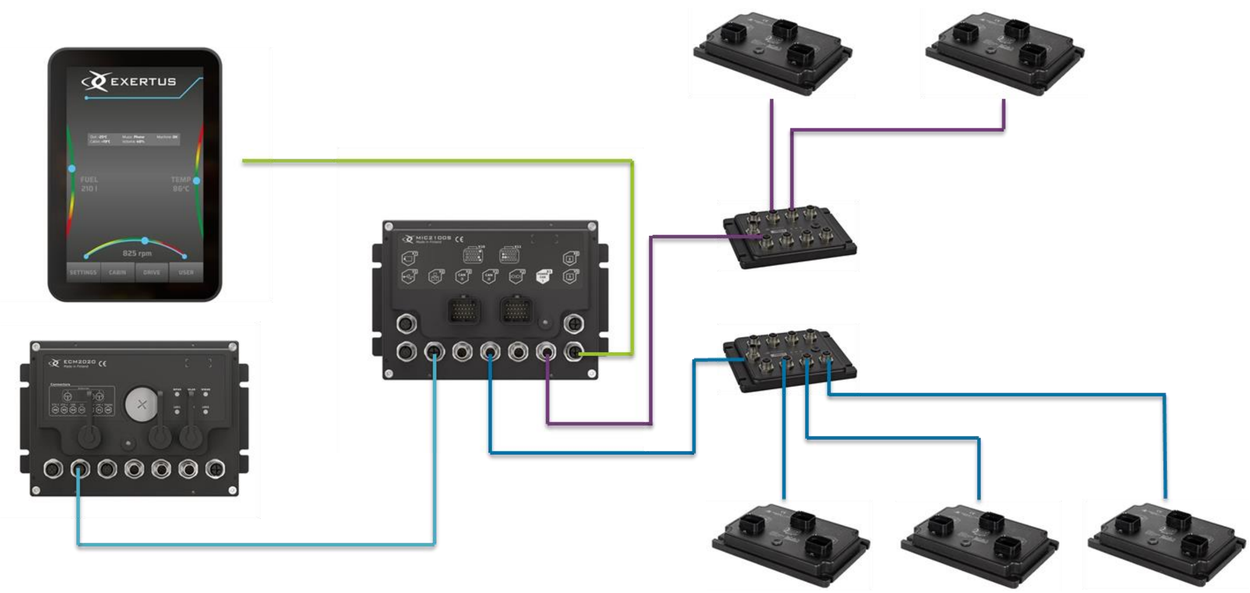

Figure 3 Exertus architecture of BB4, master controller with peripheral devices

3.4.5 Identified shortcomings

Shortcomings are identified at many places. At the Digital Twin layer, BB4 will enhance quality checks, alarm detection and recovery in order to further increase automation and efficiency. At the edge layer, BB4 will enable modular and efficient application development of on-board machines. In between, BB4 will facilitate reliable multi-machine communication (M2M). BB4 will also facilitate the necessary intra- and interprocess communication and the ability to take advantage of multithreading or parallel computing on multiple cores. This includes a framework that allows integration of generated and/or legacy code from external origins (such as Simulink models). BB4 also provides a flexible Hardware Abstraction Layer to accommodate projects with different hardware connections (like EtherCAT).

There is a clear lack into the identified platform solutions landscape (current market, coming trends, and partners solutions); it is related to a single platform which seamlessly integrates all the requirements for the BB4: real-time processing and communications, vast data processing capabilities, advanced features to speed-up ML/AI applications required operations, multi-core approach, heterogeneous L2-L3 communication plane, modularity, reconfigurability, etc. It is a need to create such platform; and that it is going to be at task 3.3.

3.4.6 Potential IMOCO4.E progress beyond SotA

3.4.6.1 General

Definitions and investigations of novel approaches that are not already known in the shop floor. These should help to answer to still unanswered questions such as (in particular):

- How to correctly classify an alarm when the available training set is greatly unbalanced (i.e. number of fine products N >> M products to be discarded)?
- Given an alarm, how is possible to identify automatically the best countermeasure to perform?
- How can I model my machine in order that components designed independently can be considered correctly interconnected to evaluate the cause-effect chain of a given level of quality reached in a given production stage?
- FPGA based SW acceleration for ML/AI advanced applications (video and other possible, close related to the industrial plant), leveraging on Xilinx Deep Learning Processor Unit (DPU), a programmable engine dedicated for convolutional neural network execution.

In IMOCO4.E we are expected to further extend this concept, by moving to embedded architectures (ARM) and also taking into account AI computations.

The STM32H7 line of chips could be an interesting alternative for the weaker STM32F4 products. Xilinx Zynq UltraScale+ MPSoC and Versal architectures bring as well a great potential to the table, as they combine a mlti-core CPU with a cutting-edge FPGA in the same die, exploding the CPU co-processing and offloading concept to the maximum.

3.4.7 Applicable standards, methods, tools

Standards:

- EtherCAT: IEC 61158
- ISO/OSI reference protocol stack, EtherCAT, ProfiNET, DDS, TNS over Ethernet, OPC-UA, MQTT, Volere Approach for requirement definition.
- EtherCAT Master and TSN.
- IEEE 802.1 TSN-Time-Sensitive Networking- standard; in fact, it is a bundle of different standards below it.

Methods and tools:

- **Xilinx Vivado Design Suite**, for developing FPGA design, a software suite produced by Xilinx for synthesis and analysis of hardware description language designs. FPGA part designs.
- **Xilinx Vitis unified Software Platform**, a comprehensive core development kit to seamlessly build accelerated applications. CPU-FPGA codesigns.

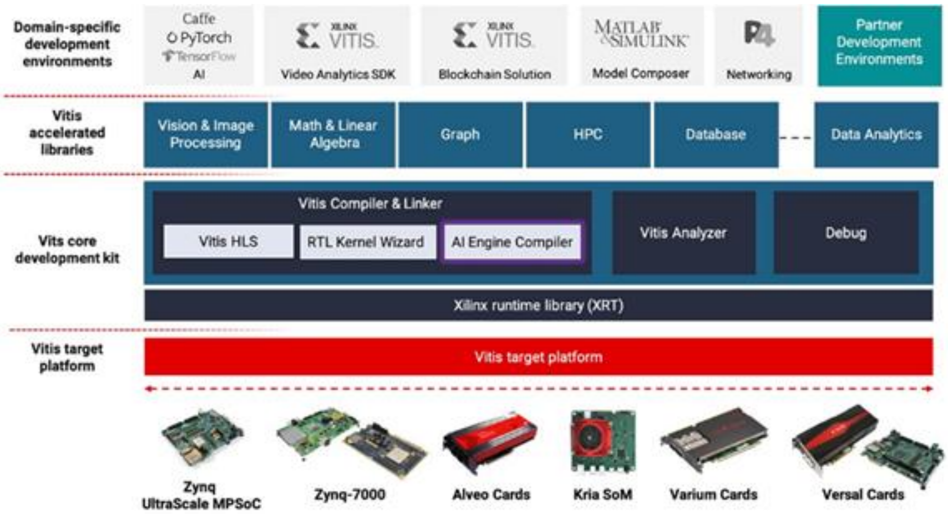

Figure 4 Xilinx Vitis ecosystem snapshot

3.5 BB5 Smart control algorithms library

Building block 5 constitutes a framework for smart control algorithms. The framework covers key solutions for mechatronic systems, ranging from feedback algorithms including vibration damping, force control, predictive control, and robust control, towards data-driven learning algorithms, covering repetitive control, iterative learning control, and machine learning algorithms. Both centralized or SISO (Task 4.3) and decentralized or MIMO (Task 4.4) controllers are included in BB5.

3.5.1 Market scan, COTS solutions (high TRL)

Libraries for motion control applications can be found within main controller manufacturer functionalities (SIEMENS Simatic, Beckhoff TwinCAT 3). However, these libraries only cover basic control functions (PID cascade control). A library compiling advanced motion control functionalities has not been identified in the market (neither at research level).

In addition, COTS controllers for motion control applications (PLC/CNC) offer very limited functionalities:

- Cascade type controller (position, velocity, current loops) is the standard approach.
- Simple velocity and acceleration feedforward are normally available.
- Some special functions can be provided: load sharing with preload (multiple drives acting on the same DOF), gantry systems, friction and backlash compensation...
  - Heidenhain: Active Vibration Damping (AVD), position and load-dependent parameter adaptation (PAC/LAC)
  - FANUC: Dual Position Feedback (for large inertia ratios); AI Feedforward; ILC for repetitive part production; many compensations
  - NUM, GEFRAN: Active Vibration Control
  - Schneider, GEFRAN: anti-sway for crane applications
  - Elmo (EAS2): compensation of known dimensional errors

Robotic system control supposes a great challenge. In industrial manipulators, with high repeatability, positioning accuracy is not enough for new raising applications linked with manufacturing (e.g. machining). As position control loop is normally closed at the motor encoder of each joint, which has a limited stiffness (due to huge reduction ratios), poor positioning accuracy is achieved. In addition, as for conventional COTS controllers, the availability of control functionalities for controllers of industrial robots is even more limited. In recent years, some functionalities are appearing in the market:

- Staubli Unival Drive: possibility to feed joint setpoints from conventional controllers (PLC/CNC), where ad—hoc algorithms could be implemented
- FANUC Learning Vibration Control

The Collaborative Robots (Cobots) market is growing rapidly from 981M$ in 2020 to 7972M$ in 2026. Currently the leader is Universal Robots (UR) with an annual revenue of approximately 230M$ but there are many other smaller and highly innovative companies competing in this market. Rethink Robotics introduced series elastic actuators (SEAs) in their joints (licensed technology from MIT). This represented a disruptive innovation that make their robots inherently safe (passive compliance) at the cost of making their control through a torque-based control scheme very challenging (and not competitive in precision compared to position driven control schemes on stiff robots). This cost on precision and accuracy was a competitive drawback in their competition with UR for the wide Cobots market. They shut down the headquarters and transferred the technology to a German start-up (now also called Rethink Robotics, from Hahn group). We will explore how to complement elastic actuators with AI modules providing them precision, thus Rethink Robotics and other companies pushing elastic or flexible robots are our main target.

With the numerous emerging applications of collaborative robots, conventional ways of robot programming are being revisited. Intuitive path planning using gestures, speech, or special purpose haptic devices are gaining popularity due to their flexibility and ease of use even by unskilled human operators without deep robotics and IT background. Examples of COTS solutions can be found in Cobots by Kuka or Fanuc. They are usually limited to execution of basic jogging motions.

3.5.2 Emerging trends (rising TRL)

As mentioned, even if COTS motion controllers offer limited advanced control functionalities, it is more and more common that they provide tools to implement own code, but with limitations and restricted to advanced users (FAGOR CNC, Beckhoff TwinCAT).

Optimization based approaches are starting to be available in COTS solutions but more in the process control side (SIEMENS INCA MPC) instead of motion control applications.

Artificial Intelligence and Machine Learning techniques seem to be gaining importance in COTS control systems. However, current functionalities do not seem to be oriented to motion control applications. For example, Beckhoff offers a generic Machine Learning module, and FANUC presented few years ago the AI ServoMonitor functionality to predict mechanical breakdowns using Deep Learning techniques. Hence, it is clear that data-based techniques are emerging, but still finding its way in critical functionalities of motion control systems.

Regarding cobots, Serial Elastic Actuators (SEAs) and related innovations (for instance patents: US20120312114A1, WO2013155031A3) was a technology breakthrough and other elastic joint actuators are being developed (for instance patents: US8291788B2, WO2015023340A3, US20100253273A1, EP2989345A1, US201901226498A1, WO2015191585A1, US9506455B2, WO214001585A1) to further reduce the cost and increase compliance (instead of costly active compliance mechanisms evolved from industrial robotics). However, this higher compliance limits dynamic and accuracy performance of the robot and leads to a great challenge for motion controllers.

3.5.3 Literature & academic research (low TRL)

A vast literature research dealing with motion control strategies was provided in deliverable D4.1 of I-MECH project. Next, to avoid overlapping, a brief state of the art of recent research activities leading with specific control techniques or solutions that are targeted within IMOCO4.E is presented.

Model-based control uses a model for the design of controllers. This can be used for multiple techniques, such as robust control, multivariable feedforward and feedback control and inferential control [1]. This approach is also used for optimal tuning of conventional PID controllers as well as compensation of non-linearities [2]. Although control of conventional feed drives has been researched from a long time there are still some gaps related to specific actuators (Rack-pinion [3]) and non-conventional drive configurations (large inertia ratios [4]).

In the last few years, a lot of advances have been made in **learning control**. First, iterative learning control [5] has been developed and extended towards MIMO systems and basic functions [6]. Iterative Learning Control is a mature technology when the periodic disturbance is almost a slowly varying almost-deterministic signal. However, the performance could be improved when there are many non-strictly repetitive or iteration-varying factors. For these problems, literature provided several new methods in recent years [7][8][9][10][11]. Another area of interest is the managing of system constraints in an ILC architecture [10][12]. Furthermore, **repetitive control** (applicable to both reference tracking and disturbance rejection) has been researched since the 80s [13]. Current developments in repetitive control include multi-period repetitive control [14] and machine learning techniques (see BB8). Black-box techniques learning (inverse) finite impulse responses are getting traction as well, see for instance [15].

Vibration compensation is crucial in most mechatronic applications, as in elevator control (especially in tall buildings installation). Following this example, the elevator should reach high speed and acceleration while keeping the users comfortable. Advanced algorithms for compensating vertical and horizontal vibrations have been proposed in literature [16][17][18][19][20]. Of course, vibration control is a wide research area as vibration frequencies and amplitude of different magnitudes can be presented and damping requirements can be also different depending on the application.

Artificial Intelligence and machine learning techniques are meant to be critical in control systems [21] especially for complex, nonlinear systems that are hard to model with traditional methods. Data-driven methods are better suited for such systems. Mostly, these AI applications are focused in high-level control layers (3-4), like predictive maintenance (BB6), manufacturing optimization or path planning in robotic applications (BB10). AI based control approaches (CNN, RNN, etc...) have been researched in recent years for different applications, although their application in COTS for motion control applications is not extended yet:

- Identification and tuning algorithms (both static and on-line) [22][23]
- Compensation of non-linear disturbances [24]

There are three different levels in which AI is applied in control problems, from low-level to high-level: (1) system identification, (2) control policy approximation, (3) control policy learning. We will address the mean research directions at these three levels below:

System identification

In system identification, a plant model is identified through data-driven techniques. For many applications, differentiability of the model is also a design objective. Physical models often support the data-driven techniques, depending on the available knowledge of the plant and the required extrapolation capacity, yielding white-box, grey-box and black-box models.

Modern regression techniques from machine learning, such as the eigensystem realization algorithm, dynamic mode decomposition, genetic programming, and sparse identification of nonlinear dynamics (SINDy) are examples of data-driven system identification techniques. These techniques can be extended with model order reduction techniques, to make the models manageable for (real-time) control purposes. Additionally, one can also cast the system as a probabilistic model and obtain explicit descriptions of uncertainty through approximate Bayesian inference.

There is also a trend to train deep neural networks, such as deep autoencoders, to represent the system dynamics, because of their excellent expressive capability for non-linear functions. In such case, the system will have a neural state space, and the dynamics in the latent space of the neural network might be of a much lower dimensionality, making them more efficient for control purposes.

All these machine learning methods serve as an enabler for advanced model-based (optimal) control.

Control policy approximation

Optimal control finds advanced controllers that optimize some objective function. Model Predictive Control (MPC) is an example of optimal control, which is especially popular because it enables to optimize control inputs for some cost over both inputs and predicted future outputs. Besides the need for accurate system models, optimal controllers are challenged by their heavy computational requirements, as they require an optimization problem to be solved at each time step.

Explicit optimal control (e.g., explicit MPC) finds an expression for the optimal control policy, given an input condition, and can thus be very efficiently applied in real-time. Where analytical solutions are impossible, the control policies can be precomputed for any input condition. Precomputation, however, suffers from the curse of dimensionality, and becomes intractable for with increasing system size, with varying input conditions, with nonlinear systems or when dealing with uncertainty. To address these issues, approximate techniques (e.g., approximate MPC) have been developed, capturing the approximate solution to the optimal control problem, given an input condition, in a very efficient and condense way. They are often represented by trained deep neural networks. Much ongoing research effort investigates AI frameworks and network architectures to tackle the curse of dimensionality in explicit optimal control.

In stochastic optimal control, the uncertainty on the system dynamics is explicitly incorporated in the forward model. Future states of the system can be simulated using approximate Bayesian inference, which allows for the selection of approximate control policies that are robust to uncertainty.

Control policy learning

Rather than approximating an implemented control policy, the closed-loop control law can also be directly learned. This requires access either to data from parametrized closed-loop controllers, or to an evaluable (and potentially differentiable) closed-loop system consisting of a parametrized controller and a plant. The plant can either be real or simulated, as a digital twin. While this latter option is attractive to learn a control policy, it leaves the sim-to-real gap to be closed.

With the above elements in place, the parameters in the control law can be optimally tuned according to an objective function. Many recent research papers rely on machine learning techniques like genetic algorithms/programming and reinforcement learning to optimize these control policies. Beyond that are AI systems that use probabilistic forms of reinforcement learning to directly learn a control policy from noisy observations and uncertain system dynamics.

3.5.4 Partner solutions (any TRL)

Some of the potential solutions are listed next:

- Learning and repetitive control algorithms (TUE)
- Impedance control in industrial manipulators applied through an industrial controller (TEK)
- High-performance control of cobots (UGR)
- Non-linear compensations of linear feed drive systems (friction, backlash, cogging...) (FAG)
- Semi-automatic axis identification and tuning tools (UWB)
- Digital Twin for machine and CNC simulation (FAG)
- Anti-rollback and vibration compensation for lift (GDM)

- Feedforward and feedback antisway control for cranes (UWB)
- Passive vibration damping using input shaping (UWB)
- Image processing related algorithms for implementation in co-located control systems (TNO)

3.5.5 Identified shortcomings

COTS controllers for motion control applications (PLC/CNC) offer very limited advanced control functionalities and some of them do not present means to properly implement ad-hoc functionalities. For example, impedance control application in robot manipulators is limited as most manufacturers do not even allow controlling joint drives at a proper rate.

In addition, COTS solutions and required licenses are usually very expensive. On the other hand, open source and free tools not very useful sometimes.

Although learning control has increased a lot the last few years, by for instance adding (rational) basis functions, learning control for complex (linear parameter varying, multi-rate, etc.) systems can still be improved. This can be explained since typically black-box methods are used for these complex systems, where the known structure of the system is lost.

Although AI and machine vision algorithms have developed greatly during the last decennium, alas the emphasis on time critical and time deterministic requirements has lagged.

3.5.6 Potential IMOCO4.E progress beyond SotA

3.5.6.1 General

De-centralized control functionalities:

- New design methods for vibration damping using input shaping filters (UWB)
- Repetitive disturbance compensation with self-commissioning capability (UNIBS, UWB), addressing robustness aspects and multi-rate implementations (UWB, REX)
- Robust control (TUE)
- Model Predictive Control for mechatronic systems (MPC)
- Advanced feed drive control (TEK):
  - Modelling and compensation of non-linearities: friction, backlash (TEK, FAG)
  - Control of different types of actuators: piezo, voice-coil, stepper motors, multi-drive systems (preloaded rack-pinion) …
  - Control of unfavourable inertia ratio systems
- Improvement of robotic manipulator accuracy using additional measuring systems: secondary encoders, TCP measurement… (TEK)
- Impedance or compliant control for robot manipulators (UGR)

Centralized (multivariable) control functionalities:

- Algorithms for design of partial and fully closed-loop control architectures using auxiliary load-side sensing (UWB)

- Vision and data-driven learning (TNO)
- Intuitive robot programming using haptic devices (UWB)
- Learning gray-box LPV/parameter-dependent feedforward parameters based on data. Furthermore, next generation lightweight and flexible mechatronic systems [25] can still be improved using model-based or data-driven techniques (TUE/M)
- Optimal control for multi-axis systems with similar critical natural frequencies (crane systems, windmill platforms…)

3.5.6.2 Related to Digital Twin

As most of the proposed functionalities are model-based, linkage of BB5 with Digital Twins is strong. In this sense, white-type or physics-based Digital Twins will be a key component. Of course, the physics-based Digital Twins will be also used for direct application in control algorithms (e.g. robot kinematics Jacobian in impedance control).

Grey-type Digital Twins will also be used, for example in the new learning control approaches proposed by TUE.

3.5.6.3 Related to AI and Data analytics

Although some of the functionalities to be developed in BB5 and included in the general group, some specific actions are defined under data-driven techniques:

- Drive self-commission and condition monitor: UNIBS will design repetitive disturbance compensation using digital-twin and xIL paradigms. Moreover, the controller will track and transmit main performance indexes; thus, the controller will be an information source for condition monitoring and self-commissioning module.
- AI-based adaptive control of elastic joint actuators (cobots): UGR will research for developing adaptive controller for automatically learning the inverse dynamics model of flexible cobots (with elastic components at their joints) which make them competitive when using torque-based control (for add-on safety) in terms of precision compared to position driven control approaches. This innovation is not an add-on component for a specific purpose application but rather at the core of the safe cobots technology. The innovation represents a precision enhancement engine on cobots in which safety is key (flexible robots using torque-based control) as Rethink Robotics Baxter and now Swayer robot. The innovation core format is an Artificial Intelligence (AI) software module that learns/captures and efficiently manages the inverse dynamics model (this can also be related with the Digital Twin concept). It enhances precision for torque-based control mode. It can also be of interest for second use internal applications as predictive maintenance (for instance detecting deviations of the basic model).

3.5.7 Applicable standards, methods, tools

- Matlab/Simulink will be the main development environment. Other environments, like Gazebo as simulation environment, will be also used.
- IEC61131 programming languages for PLC controllers
- FMI/FMU was selected as a standard during IMECH, but limited implementation.
- XiL-based development

- AUTOMATION-ML (digital twins and communication models...)

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3.6 BB6 Algorithms for condition monitoring, predictive maintenance and self-commissioning of industrial motion control systems

3.6.1 Market scan, COTS solutions (high TRL)

3.6.1.1 Condition monitoring based on vibration:

Brüel & Kjær Vibro – VC8000 – Vibration analyser with RUL estimation capability.

3.6.1.2 Power inverter and electric motor condition monitoring

The predictive maintenance of electric motors and inverters is not being implemented as a standard functionality in industrial/commercial environment in electric drives systems. Advanced testing of electric motors is usually provided as a service of specialized companies:

- Motor Diagnostic Systems, Inc., provides off-line and on-line testing electric motors using standard measuring apparatuses (oscilloscopes, data loggers, analysers, etc.) as a service
- SCHLEICH GmbH - MotorAnalyzer2 R2 – expert level tester for electric motors – off-line testing

The predictive maintenance of electric inverters is not being implemented as a standard functionality in industrial/commercial environment.

3.6.1.3 Tools for condition monitoring app development

MATHWORKS – Predictive maintenance toolbox (module of MATLAB) The toolbox provides functions and an interactive app for exploring, extracting, and ranking features using data-based and model-based techniques, including statistical, spectral, and time-series analysis. Survival, similarity, and trend-based models can be used to predict the system's time to failure (RUL).

3.6.2 Emerging trends (rising TRL)

The evolution in the field of hardware which supports parallel data processing enables to employ the ANN or AI in general for the diagnostics, fault detection and remaining useful life (RUL) estimation. These devices or microcontroller peripheries provide huge computational power which enables to move these data processing algorithms on the edge device and thus reduce the required communication bandwidth.

3.6.3 Literature & academic research (low TRL)

A strong effort is noticeable in the field of condition monitoring and predictive maintenance in various subsystems of electric drives. The proposed solutions can be divided into areas of condition monitoring of mechanical systems, electric motors and power electronics system condition monitoring.

The prognosis for power modules failure is still in its early stages and is the subject of many academic and industrial studies. However, two main approaches are significant. The first one is based on failure mechanisms. It could be based on physical of failure models, empirical ones, or test data. The second one is based on failure precursor parameters such as temperature sensitive electrical parameters (TSEPs) and extrapolation methods such as regressors or neural networks, etc.

3.6.4 Partner solutions (any TRL)

BUT has a knowledge of 6 phase electric drives. This type of drives provides a built-in redundancy which allows drive operation under some fault condition with limited performance. It contributes to electric drives reliability. The types of the drives were experimentally verified in BUT laboratories. Primary use of the drives is supposed in the electric vehicles.

3.6.5 Identified shortcomings

Multiphase drives require special hardware, i.e. motor, inverter and controller. They also require special software for the control of multiphase drives, for the diagnostics and for the control during functional fault. The redundancy concept leads to the utilization of more components and thus to higher complexity.

3.6.6 Potential IMOCO4.E progress beyond SotA

Complex condition monitoring methods of electric drives can be considered as crucial commitment to IMOCO4.E progress beyond the SotA. The complex condition monitoring should include faults and degradations of power inverter components, e-motor, and mechatronic system as well. Multiple sensors data can be potentially analysed using methods of AI to identify individual fault progress.

3.6.6.1 General

The BUT plans performing a set of experiments of IGBT modules and DC link capacitors accelerated ageing. The specified faults progress will be accelerated till the component damage. The important quantities will be measured during the experiments. Condition indicators methods will be derived for individual faults progress observed in real systems based on the measured data analysis.

3.6.6.2 Related to Digital Twin

Model based condition indicators suppose using models for deteriorating parameters estimation. These models implemented in condition indicators algorithms can be considered as digital twins of individual drive components.

Condition monitoring algorithms can be developed/learned on digital twins in cases of nonexistence of data from real systems. Obtaining data for algorithms development is one of crucial problems in condition monitoring and predictive maintenance algorithms development.

3.6.6.3 Related to AI and Data analytics

The condition monitoring and predictive maintenance of electric drive as a complex system with many sensors providing a huge amount of data and with wide set of components potentially causing faults is a field for data analytics approach and AI based condition monitoring methods. Data from various domains can be gathered and analysed. Mechanical, electrical, thermal, acoustic, optical domains are going to be involved. Condition indicators methods, RUL estimation methods and decision strategies can utilize these approaches.

3.6.7 Applicable standards, methods, tools

IEEE Std 1856TM-2017 - IEEE Standard Framework for Prognostics and Health Management of Electronic Systems

ISO 13374-2, Condition monitoring and diagnostics of machines — Data processing, communication and presentation — Part 1: General guidelines

ISO 13374-2, Condition monitoring and diagnostics of machines — Data processing, communication, and presentation — Part 2: Data processing

ISO 13374-3, Condition monitoring and diagnostics of machines — Data processing, communication and presentation — Part 3: Communication

ISO 13379, Condition monitoring and diagnostics of machines — General guidelines on data interpretation and diagnostics techniques

ISO 13379-1, Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines

ISO 13381-1, Condition monitoring and diagnostics of machines — Prognostics — Part 1: General guidelines

ISO 17359, Condition monitoring and diagnostics of machines — General guidelines

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3.7 BB7 High performance servo-drives

Miniature DC servo drive with advanced motion control features and EtherCAT communication, with possibility to add custom control algorithm into the drive firmware.

3.7.1 Market scan, COTS solutions (high TRL)

Most known high-performance servo drive solutions adopt the EtherCAT standard. Typical servo and fieldbus update rates are up to 20kHz. Beckhoff drives the Ethercat standard (Ethercat.org) and provides a family of high-end servo drives (AX5000, AX8000). Other companies with similar offerings are Omron (including formerly Delta Tau), ACS, Elmo motion control, Prodrive Technologies, Advanced Motion Control.

UWB research and development team has several years of experience with developing experimental robotic manipulators and develops its own miniature servo drive with EtherCAT communication with intended use in collaborative robotics.

Market scan of miniature, low power, dc servo drives with advanced motion control features and EtherCAT communication, suitable for application on the field of collaborative robotics, leads to several servo drives manufacturers, whose below described products match our search criteria.

Those manufacturers are:

1. ELMO Motion Control Ltd. (Israel),
2. INGENIA-CAT, S.L. (Spain),
3. ADVANCED Motion Controls (USA).

ELMO Motion Control has three dc servo drive product lines, named The Platinum, The Gold, The SimplIQ. As a reference product we can take the Platinum Solo Twitter drive, which has compact dimensions with footprint 52 x 37,9 mm and EtherCAT communication. The drive is available in various configurations. As we are mainly concerned in miniature low power drives, we take as a reference drive the variants with nominal supply voltage of 85V and RMS current limits of 0.7 / 2.1 / 4.2 / 7.1 / 10 / 17.7A. Another important feature is the possibility to implement user control algorithm directly into the drive's firmware. ELMO Motion Control provides this functionality, for all drives from Platinum product line, through the ability to incorporate the code generated with Math works Embedded Coder® into the drive system.

https://www.elmomc.com/product/platinum-solo-twitter/

Figure 5 "Platinum Solo Twitter" DC servo drive (ELMO Motion Control)

Another significant manufacturer of miniature dc servo drives is Ingenia. Ingenia's EVEREST and CAPITAN dc servo drive product line represent one of smallest dc servo drives on the market. CAPITAN XCR has dimensions of 42 x 29 x 19 mm and EVEREST XCR 42 x 29 x 23.2 mm. CAPITAN servo drive operates on voltages from 8V to 60V with maximum 10A continuous current. EVEREST servo drive operates on voltages from 8V to 80V with maximum 45A continuous current. Ingenia's CAPITAN and EVEREST servo drives represent high performance miniature dc servo drives with EtherCAT communication, without the ability to incorporate custom control algorithm directly into the drive firmware.

https://ingeniamc.com/servo-drives/capitan-xcr-panel-mount-ethercat/

https://ingeniamc.com/servo-drives/dc/canopen/everest-xcr-30a-80v-panel-mount/

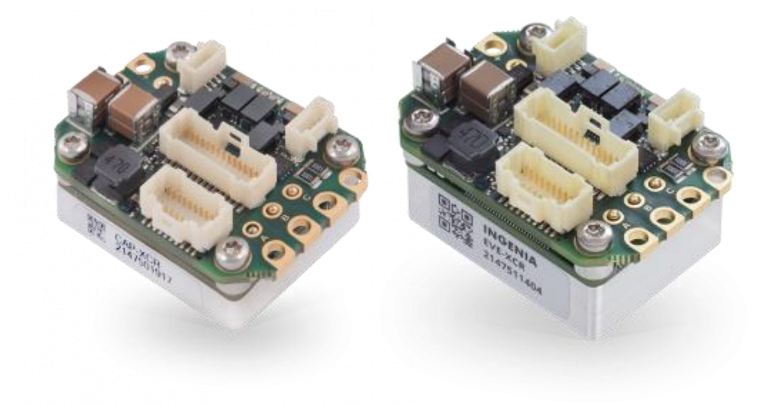

Figure 6 "CAPITAN XCR" (left) and "EVEREST XCR" (right) DC servo drives (Ingenia)

Third selected manufacturer of dc servo drives of our interest is Advanced Motion Controls. Advanced Motion Controls FM100-50-EM dc servo drive features low dimensions of 50.8 x 43.2 x 26.9 mm, EtherCAT communication, operating voltage range from 20V to 90V and continuous current of 50A. This drive don't allow custom algorithm incorporated directly into the drive firmware.

Figure 7 "FM100-50-EM" dc servo drive (Advanced Motion Controls)

Only one of three selected miniature dc servo drive manufacturers allows incorporation of custom control algorithm directly into the drive firmware, which is one of targets for our dc servo drive development together with implementation of repetitive control methods into our drive.

3.7.2 Emerging trends (rising TRL)

Here we'd like to mention the ELMO Motion Control's approach of adding custom control algorithm directly into drive's firmware through generation of relevant program and its integration into the drive firmware by the user. The description of this feature can be found on the link below.

https://www.elmomc.com/PPT/EMC2_2021/index.html

We believe that this is a new and perspective approach. We would like to focus on this approach, and to implement similar approach into our dc servo drive. With this functionality, the user will be able to implement various control algorithms into the drive itself. This can be useful for solving special use cases, and to provide certain degree of autonomy to the drive itself.

Beckhoff and EtherCAT.org are working towards release of the EtherCAT G standard and products, facilitating lower bus latencies and greater bandwidth. Products are not yet released.

Another trend is to put the realtime critical host part (e.g. previously a dedicated motion controller or PLC) with a Windows host by means of an RTOS and/or hypervisor technologies.

3.7.3 Partner solutions (any TRL)

UWB has developed miniature dc servo drive with EtherCAT communication, intended to be used in research projects mainly focused on robotics and control applications. The servo drive uses Infineon XMC4800 as main system microcontroller, which is SotA solution in the area of MCU with integrated EtherCAT slave controller. This MCU is a High Performance 32-bit ARM Cortex-M4 CPU clocked on 144 MHz with 16-bit and 32-bit Thumb2 instruction set, DSP/MAC instructions, Floating Point Unit, 2MB FLASH, 352 kB RAM, beside other features.

This servo drive will be used as hardware platform for implementation of user friendly "custom algorithm build and run" functionality, allowing the user of the servo drive to define its own control algorithm and incorporate it into drive firmware. Drive firmware and configuration software tools for the drive will be further extended to allow described functionality in straightforward and user-friendly way. Drive firmware and related tools will be also extended to support full IO connectivity of the drive, to improve FOC motor algorithm with focus on applications in collaborative robotics. The drive will be used in test setup for development and testing of repetitive control algorithm. This test setup can finally serve as a demonstrator of the servo drive, its software tools and repetitive control algorithm.

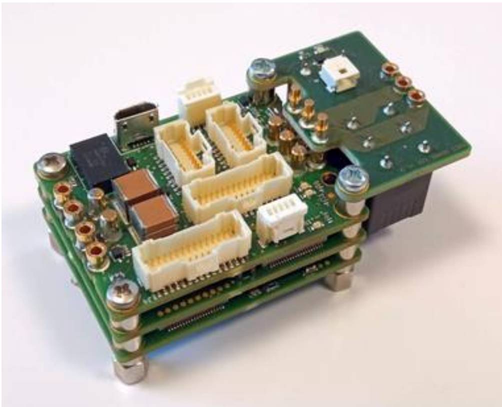

Figure 8 Miniature dc servo drive with optional relay brake board (UWB)

REX Controls is the manufacturer of REXYGEN software tools used in various fields of automation, process control and robotics. REXYGEN Studio allows graphical programming using the so-called function blocks and provides a straightforward and convenient style of programming of control algorithms. REXYGEN studio is intended to be used as a tool for definition of custom algorithm, which will be incorporated into the dc servo drive firmware.

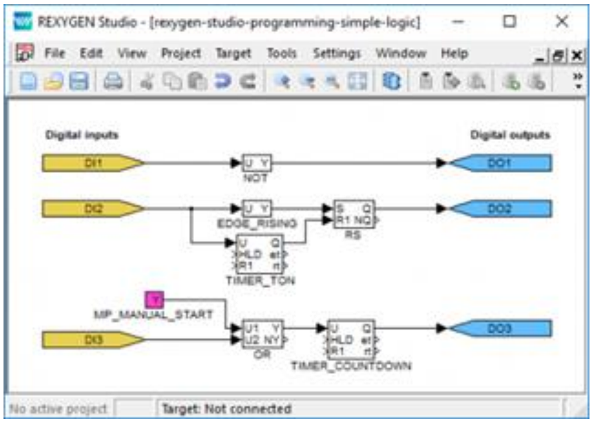

Figure 9 REXYGEN Studio software (REX Controls)

3.7.4 Identified shortcomings

There are still only few out of the box and open solutions to build a motion control system connected to a Windows/Linux master. EtherCAT is relatively open (e.g. SOEM, SOES), but building a real-time EtherCAT master within an RTOS and to configure it to run alongside Windows/Linux requires a lot of experience and knowledge.

Commercial servo drives have limited or inflexible options to stream internal signals for diagnosis, especially signals at a faster rate than the servo loop (for instance the current control signals). These signals are essential for high-quality current control tuning.

Only a few available solutions allow user defined algorithm to be directly incorporated into the drive firmware.

3.7.5 Potential IMOCO4.E progress beyond SotA

3.7.5.1 General

A miniature dc servo drive allowing user to define his own control algorithm and incorporate it into the drive firmware. Implement a repetitive control algorithm into the drive.

3.7.5.2 Related to Digital Twin

The drive will allow fast access to its internal data to allow comparison between selected subsystem of the device and its digital counterpart. This feature can be used in testing of drive internal subsystems like FOC motor control, tuning of speed and position control loops, etc.

It would be useful if a digital twin of servo drive can be directly converted into servo drive code. In that way the digital twin is single point of truth for model-based systems engineering. This means it can also be used to predict behaviour in conjunction with new motors and loads in a simulation stage. It is likely that the real system behaviour will follow closely. It is also valuable in debugging (firmware) issues even after the product is released.

3.7.5.3 Related to AI and Data analytics

AI algorithms will be not implemented directly at the very edge. However, the custom algorithm, namely distributed repetitive control is quite suitable to detect changes in the system dynamics or signals. Those can be further reported bottom-up to higher IMOCO4.E Layers and processed via methods embedded in BB8.

3.7.6 Relation to standards

IEC/PAS 62407 (Ed 1.0), *Real-time Ethernet control automation technology (EtherCAT)*

IEC 61158-2 (Ed.4.0), *Industrial communication networks - Fieldbus specifications* - Part 2: Physical layer specification and service definition

IEC 61158-3/4/5/6-12 (Ed.1.0), *Industrial communication networks - Fieldbus specifications*
- *Part 3-12: Data-link layer service definition*
- *Part 4-12: Data-link layer protocol specification*
- *Part 5-12: Application layer service definition*
- *Part 6-12: Application layer protocol specification -Type 12 elements (EtherCAT)*

IEC 61784-2 (Ed.1.0), *Industrial communication networks - Profiles*
- Part 2: Additional fieldbus profiles for real-time networks based on ISO/IEC 8802-3

IEC 61800-7-301/304 (Ed.1.0), *Adjustable speed electrical power drive systems*
- Part 7-301: Generic interface and use of profiles for power drive systems - Mapping of profile type 1 to network technologies
- Part 7-304: Generic interface and use of profiles for power drive systems - Mapping of profile type 4 to network technologies

ISO 15745-4:2003/Amd 2:2007, *Industrial automation systems and integration -- Open systems application integration framework*
- Part 4: Reference description for Ethernet-based control systems

SEMI E54.20-1108 - *Standard for Sensor/Actuator Network Communications for EtherCAT*

IEC 61784-3 Industrial communication networks - Profiles
- Part 3: Functional safety fieldbuses

IEC 61784-5 *Industrial communication networks* - Profiles
- Part 5: Installation of fieldbuses

EN 50325-4 Industrial communications subsystem based on ISO 11898 (CAN) for controller-device interfaces - Part 4: CANopen

EN/ISO 13849-1 Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design

3.7.7 References

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3.8 BB8 AI, Machine learning, deep learning algorithms (real-time part)

3.8.1 Market scan, COTS solutions (high TRL)

Task-specific automation is available for some of industry processes, but its implementation in industry usually requires additional development activities. Open-source computer vision models such as object detector **YOLOv5** (https://github.com/ultralytics/yolov5) are available for finetuning and adoption to different task, while requiring some expertise in machine learning and collection of training data. Now there are several commercially available services such as **Pickit3D** (https://www.pickit3d.com/en/) and **Photoneo** (https://www.photoneo.com) that automate wider range of industrial processes by adding computer vision and AI. The automation is usually based on the perception capabilities and the robot control is done separately still requiring a significant amount of time spent on robot programming activities.

3.8.2 Emerging trends (rising TRL)

Solutions are emerging that try to learn not only the perception capabilities of robots but also to learn actions. **Covariant Brain** (https://covariant.ai/) claims universal AI that allow robots to learn general abilities such as robust 3D perception, physical affordances of objects, and real-time motion planning. While **Microsoft Project Bonsai** (https://docs.microsoft.com/en-us/bonsai/product/) is a low-code AI platform that simplifies machine teaching and incorporates deep reinforcement learning.

3.8.3 Literature & academic research (low TRL)

3.8.3.1 Reinforcement Learning

Reinforcement Learning for robots in simulators is well researched topic in AI [1][2][3][4]. Overcoming the gap between simulation and reality and successfully transferring perception and action learned in simulators to real robots in real environments (Sim2Real) is a newer branch of AI, combining conventional supervised deep learning, reinforcement learning, visually and physically realistic simulators, and other novel approaches [5][6][7][8][9].

3.8.3.2 Knowledge Distillation

In machine learning, knowledge distillation (KD) is the process of transferring knowledge from a large model to a smaller one [10].

Knowledge distillation transfers knowledge from a large model to a smaller model without loss of validity. As smaller models are less expensive to evaluate, they can be deployed on less powerful hardware (such as a mobile device) [11].

A larger model is trained using all the available data to learn concise knowledge. The smaller model is not able to learn the same knowledge from the data, therefore, to distillate knowledge, the smaller model is trained to learn from the soft output of the large model.

Knowledge distillation consists of training a smaller network, called the distilled model, on a dataset called transfer set (different than the dataset used to train the large model) using the cross entropy as loss function between the output of the distilled model and the output produced by the large model on the same record, using a high value of softmax temperature for both models [11].

There are three main components to KD [12]:

- Teacher-Student-Architecture
- Knowledge Type
- KD Algorithm

There are three main forms of knowledge that are used for KD [12]:

- response-based knowledge
- feature-based knowledge
- relation-based knowledge.

3.8.3.3 Online continuous learning models

Data-driven models may be trained once to predict, for instance, remaining useful life of a machine. However, motion control systems are often dynamic; their physical behavior is ever-changing. Models trained one time on a static dataset are also called 'offline' learning models. However, online learning models are designed to continuously update the model to improve itself dynamically over time [13].

There are several methods [14] to deploy an AI or data-driven model, like this non-exhaustive list of three deployment methods:

- Embedding a model directly into a system in remote or mobile context.
- Treat each model as a microservice in a Docker container when using a model in a server-side context.
- Deploy a model on a server to build and manage models. This can be executed on-premise or in the cloud.

3.8.4 Partner solutions (any TRL)

In our IMOCO partner "Madara Cosmetics" human manual picking and placing of differently oriented bottles on manufacturing lines conveyor replacing with robot RL vision-based sim-to-real learned pick-and-place.

EDI already has a smart robot fine-tuned to work on a pick and place task. It includes AI-based vision component and trajectory planning module. EDI also have developed synthetic data generation approaches, which alleviate the data acquisition and labelling needs to a degree and is a step towards easy re-trainable system.

3.8.5 Identified shortcomings

Current partner solutions (EDI pick & place robot) and market ready SotA approaches can be fine-tuned to a specific task, but in a use-case defined by partner MADARA, where robot has to manipulate many different objects, pick them from differently packed boxes, and has to be able to easily learn new objects, the current approaches require a lot of manual labelling and machine learning expertise. EDI's synthetic data approach still requires some data acquisition, because of the gap between real and generated data. Also, current approach allows robots to learn perception but not action

3.8.6 Potential IMOCO4.E progress beyond SotA

Sim2Real research and development by EDI should ease the usage of Reinforcement Learning to train and fine-tune the robot to work with different objects and tasks. Complete and successful transfer of perception of actions learned in a simulator would be a significant step towards cheaper, safer, and faster training of smart robots. Even a partial success would progress beyond SotA, by reducing (not fully eliminating) the training needed in a real environment with a real robot.

Nuromedia plans to develop new models to track and predict the behaviour of humans in the environment of the robot. The benefit of such models is twofold. In the simulator such models can be used to create more realistic human movement. In the real world, the predictions of human behaviour are improved and by incorporating that into the control of the robot, also the security of human-robot interactions are improved.

3.8.6.1 General

Reinforcement Learning in the simulation transferred to a real robot demonstrator working on a real production line would ease the deployment of AI for different industry tasks. With such Sim2real transfer module, any future progress in relevant AI algorithms (RL, perception) will directly translate into improvements in real robot operations. This would be true not only for the specific task of the pick&place demonstrator, but also for other tasks of smart industrial robots

3.8.6.2 Related to Digital Twin

Sim2real transfer developments are closely related to digital twin ambitions of the project. Same motion planning algorithms will be used to control the real and the simulated robots. The planned physical setup for Sim2real digital twinning includes: Robot Universal Robot UR5, 2-finger gripper OnRobot RG2 or Robotiq 2F-140, laboratory table (later project stages replaced with manufacturing lines located in factory premises of company "Madara cosmetics"), camera setup (RGB-D camera), bottles for picking. The twin environment will include all listed physical components implemented in simulation environment Ignition Gazebo

3.8.6.3 Related to AI and Data analytics

Several AI technologies will be applied in order to train the robot, transfer the knowledge to the real world, and build a pick & place demonstrator. Training will be done in simulated environments and several Reinforcement Learning approaches will be applied and compared. For transfer of learned perception and action to a real robot, among other methods, Generative Adversarial Networks (specifically the unsupervised cycle-GANs [13]) will be used. This is one of the solutions to deal with discrepancies between the images rendered in simulation and the real robot camera observations. Novel methods of creating synthetic but realistic training data will be developed and several datasets for training perception models will be generated during the project

3.8.7 Applicable standards, methods, tools

For RL developments and training, a novel simulation environment **Ignition Gazebo** will be used. Virtual RGB-D camera will provide RGB image and depth map simultaneously, using **OGRE2** rendering engine. Several RL approaches will be applied to learn actions in a simulation. **ROS2** middleware will facilitate communication among the primary nodes of the system (RGB-D data streams, requests from motion planner and Ignition Gazebo environment) with underlaying socket-based transport interface. **MoveIt 2** motion planning framework will be used to control both simulated and real (**Universal Robot UR5**) robots

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3.9 BB9 Communication protocols and cyber-security tools

BB9 aims to offer a thorough cybersecurity framework for Industrial IoT systems, focusing on secure communications and data exchange and especially feedback systems deployed in IMOCO4.E. The work within this BB will facilitate interoperability between IMOCO4.E modules in terms of secure data communications: It will provide secure and trustworthy data management aggregated from novel sensors (BB3) and exploited by FPGAs (BB1), by the IMOCO4.E real time smart control platform (BB4), and the high-performance servo-drives (BB7). Moreover, it will facilitate fast and secure accessibility to data for the IMOCO4.E AI components (BB8) and algorithms (BB5, BB6).

Regarding BB9's position in complex Digital twins, it will ensure the deployment of all the necessary cyber security mechanisms (i) with respect to real-time synchronization and communication with digital twins and (ii) in the operation of the IMOCO complex digital twins' systems. As for BB9's relation to AI edge-to-cloud vertical deployment, it will provide cyber security technologies facilitated by AI-based anomaly detection mechanisms and will exploit federated learning approaches (AI edge-to-cloud deployments) to ensure multi-level cyber security assurance.

3.9.1 Market scan, COTS solutions (high TRL)

Cybersecurity is a generic term that covers a broad range of properties that a computer system connected to the network should embody to be considered not vulnerable to arbitrary security threats. The variety of cyber threats, which depend on the type of the computing system and its exposed functionalities, dictates the variety of tools that are available to prevent or counteract an undesired security breach of a computation system. Usually, a layered security approach is implemented in production environments, which is carefully tailored to the particular type and use cases of the systems involved. Some of the attributes of a computing system that affect the design of a complete cybersecurity solution are: (i) network access, (ii) exposed interfaces, (iii) human access (physical and remote), (iv) underlying hardware, (v) underlying software and (vi) criticality of the system. The levels of protecting a system from cyber threats are the following:

Prevent: Design the security approach, by auditing of systems and isolating entities and interfaces in private networks, ensuring that systems are up-to-date in terms of hardware and software versions employed, employing sophisticated authentication, authorization and encryption techniques for accessing entities and exchanging information.

Detect: Build a complete and exhaustive environment of agents monitoring the system under inspection in real time, provide the necessary processing and visualizations of the monitoring data for an administrator to easily follow and gain insights about the state of the system, establish sophisticated AI and ML mechanisms to automatically detect or predict anomalies and create appropriate alerts.

Counteract: Employ techniques for intervening to the system, provide alternative ways of offering the system's functionalities, carefully backing up the system's state.

As a result of the variety of threats emerging on a daily basis for every system connected to the network and of the levels of action of a cybersecurity system a plethora of tools, both open source and commercial are available on the market.

Commercial Cybersecurity Tools

In the table below, a list of commercial tools for cybersecurity is presented. Their characteristics in terms of the devices where they can be installed and their functionalities to fulfil their preventive, detecting and counteracting goals are also noted.

Table 1: Commercial Cybersecurity Tools [1]

Product	Deployment	AI/Machine Learning	Behavioral Analytics	Endpoint Management	Incident Management	Vulnerability Scanning
Acronis Cyber Protect Cloud	🖥 📱 ☁	✓	✓	✓	✗	✓
SpamTitan	🖥 ☁	✓	✓	✓	✗	✗
WebTitan	🖥 ☁	✓	✓	✓	✓	✓
Boxcryptor	🖥 📱 ☁	✗	✗	✓	✗	✗
ManageEngine Log360	🖥 ☁	✓	✓	✓	✓	✓
VaultCore	🖥 ☁	✗	✗	✓	✓	✗
SecureAnywhere	🖥 📱 ☁	✓	✓	✓	✗	✓
Keeper Business	🖥 📱 ☁	✗	✓	✗	✗	✓
BooleBox	🖥 📱 ☁	✗	✗	✓	✗	✗

Free and Open-Source Cybersecurity Tools

Cybersecurity tools corner a large market share of open-source software. There are plenty of free and open-source cybersecurity tools that meet requirements for enterprise-grade security software. Free and open-source security tools often do not provide the full range of capabilities of their commercial counterparts, although in some cases commercial licenses bringing additional functionalities are available. The power of the open-source software, thought, lies in the opportunity of creating tailored-made cybersecurity systems to meet specific needs and requirements. Small to midsize enterprises often use a combination of free and paid open-source tools to improve their organization's cybersecurity and modify their employed solution to protect their digital assets and networks according to their unique business operation needs. A non-exhaustive list of open-source cybersecurity software tools is tabulated below [2]:

Kali Linux www.kali.org	• Kali Linux is an open-source, Debian-based Linux distribution geared towards various information security tasks, such as Penetration Testing, Security Research, Computer Forensics and Reverse Engineering. • It is one of the few hacking-focused Linux distributions that comes pre-packaged with tools for reconnaissance and delivering payloads, as well as several other penetration-testing utilities. • Kali uses WSL (Windows Subsystem for Linux), which allows users to run Linux executable files directly from a Windows 10 system. • The Kali OS supports embedded devices such as Raspberry Pi, Beaglebone, Odroid, HP & Samsung Chromebook as well as well as Android OS.
KeePass https://keepass.info/	• KeePass is a free and open-source password manager that securely stores passwords. This security tools enables users to have a single place for their unique passwords for websites, email accounts, webservers, or network login credentials. • KeePass works by storing passwords in a secure database, which unlock by entering a single master key. Database encryption is using the most secure encryption algorithms available: AES-256, ChaCha20 and Twofish. It encrypts the complete database, which means usernames, notes, etc. are being encrypted along with the password fields.

Metasploit Framework www.metasploit.com/	• Metasploit Framework is an exploitation and vulnerability validation tool that you can use offensively to test your systems for known and open vulnerabilities. • This open-source security tool is helping you to divide the penetration testing workflow into manageable sections, while you can also set up your own workflows. • It is also a tool for auditing and network port scanning, which scans approximately 250 ports that are usually exposed to external services. An auto-exploitation feature works by cross-referencing open services, vulnerability references and fingerprints to find corresponding exploits.
Nikto cirt.net/nikto2	• Nikto is a free and open-source web server scanner, which scans web servers for multiple vulnerabilities. The testing covers more than 6,700 potentially harmful files/programs and makes checks for outdated versions of over 1,250 servers. The web server scanner finds version-specific problems on over 270 servers. • Users can also perform checks for server configuration issues such as the presence of multiple index files, HTTP server options. This open-source security tool identifies installed web servers and software as well.
Nmap https://nmap.org/	• Nmap, Network Mapper, is used for penetration testing and security auditing. It uses Nmap Scripting Engine (NSE) scripts to detect vulnerabilities, misconfigurations and security issues concerning network services. • Nmap maps network and ports before a security audit starts and then uses the scripts to detect any recognizable security problems. The app is fetching raw data and then determines a host type, type of operating system (OS) and all the hosts available within the network. • Network administrators can use Nmap also for performing tasks around network inventory, service upgrade schedules and monitoring uptime. • The open-source security tool runs on Linux, Windows and Mac OS X. It is designed specifically for scanning large networks but can be used to scan single hosts.
OpenVAS https://www.openvas.org	• OpenVAS is an open source and full-fledged vulnerability scanner, free for use. Users can perform unauthenticated testing and authenticated testing for various high level and low level Internet and industrial protocols. • This tool also enables performance tweaking for large-scale scans. Users can perform any type of vulnerability test by taking advantage of its internal programming language.

OSSEC https://www.ossec.net/	• OSSEC is an open source, scalable and multi-platform Host-based Intrusion Detection System (HIDS), whose creators want to keep free for the foreseeable future. • Use OSSEC on premise and in the cloud for the purpose of server protection or as a log analysis tool that monitors and analyzes firewalls, IDSs, web servers and authentication logs. • OSSEC can withstand cyber-attacks and system changes in real-time utilizing firewall policies, integration with third parties such as CDNs and support portals. The application features self-healing capabilities and provides application and system-level auditing for compliance with many common standards such as PCI-DSS and CIS.
Security Onion https://blog.securityonion.net/	• Security Onion is a Debian-based Linux distribution for detecting threats, enterprise security monitoring and log management. It incorporates security tools such as Elasticsearch, Logstash, Kibana, Snort, Suricata, Zeek, OSSEC, Wazuh, Sguil, Squert, NetworkMiner and others to protect an organization against cyber threats. • It is an all-in-one open-source security solution that provides users with various tools to detecthttps://blog.securityonion.net/ threats and monitor their systems.

Device connectivity/management and data processing/analytics Tools and Platforms

Many COTS solutions exist that provide device connectivity/management and data processing, analytics and visualization, like:

- Thingsboard & Trendz Analytics, Kaa IoT Platform, Coiote IoT Device Management, Cumulocity IoT, Friendly One-IoT, and IoT-Ticket

These all have a large customer base. Although they provide the same kind of solution there is a difference in available features and the licence model (including costs).

Other competing solutions can be found in the domain of rapid application development (no/low code), like:

- Mendix – An all-in-one Low-code Platform, with modules for App Development, Cloud, Multi-Experience, Artificial Intelligence, Intelligent Automation and Data Integration
- Betty Blocks – A no-code platform, and alternative to Mendix
- OutSystems – Another alternative to Mendix

3.9.2 Emerging trends (rising TRL)

A flurry of new threats, technologies and business models have emerged in the cybersecurity space as the world embraced a remote work model where there's no network perimeter and more applications and data in the cloud than ever before. Below, new emerging cybersecurity trends [3] are listed:

Extended Detection and Response (XDR)

Extended detection and response (XDR) centralize security data by combining security information and event management (SIEM); security orchestration, automation and response (SOAR), network traffic analysis (NTA), and endpoint detection and response (EDR). Obtaining visibility across networks, cloud and endpoint and correlating threat intelligence across security products boosts detection and response.

An XDR system must have centralized incident response capability that can change the state of individual security products as part of the remediation process, according to research firm Gartner. The primary goal of an XDR platform is to increase detection accuracy by correlating threat intelligence and signals across multiple security offerings and improving security operations' efficiency and productivity.

XDR offerings will appeal to pragmatic midsize enterprise buyers that do not have the resources and skills to integrate a portfolio of best-of-breed security products. Advanced XDR vendors are focusing up the stack by integrating with identity, data protection, cloud access security brokers, and the secure access service edge to get closer to the business value of the incident.

Secure Access Service Access (SASE)

Secure Access Service Edge, or SASE, has taken the industry by storm since Gartner debuted the phrase in an August 2019 report, with cybersecurity vendors creating new leadership roles and carrying out major acquisitions to strengthen their position around these emerging technologies.

SASE combines wide area networking, or WAN, with network security functions like secure web gateway (SWG), cloud access security broker (CASB), firewall as a service (FWaaS) and zero-trust network access (ZTNA) to support the dynamic secure access needs of businesses. SASE tools can identify sensitive data or malware, decrypt content at line speed, and continuously monitor sessions for risk and trust levels.

The SASE market crosses previously disparate technologies and demands that vendors be able to deliver these capabilities through the cloud on an as-a-Service basis. It is intended to address the security and networking needs of tomorrow as users, devices, application, services, and data rapidly shift outside the enterprise data center.

Zero Trust

The COVID-19 pandemic has accelerated the journey to zero-trust platforms as virtually the world's entire workforce was shoved outside a defined network perimeter, forcing organizations to secure end users who are working remotely as well as fix anomalies and configuration issues revealed by the new approach, according to Forrester.

A zero-trust approach to security reflects four principles: no user should be trusted by default since they could be compromised; VPN and firewalls can't do it alone since they just guard the perimeter; identity and device authentication should take place throughout the network rather than just on the perimeter; and micro-segmentation really helps minimize damage from hackers by creating interior walls and locks.

Good zero-trust platforms integrate security functions into nearly invisible tooling, Forrester said, making it so that users have no choice but to operate in a more secure fashion. The most successful zero-trust vendors can layer new functions on top of existing security infrastructure components, meaning that clients don't have to remove or replace the security investments they've already made.

Related to data processing and analytics, the following trends can be discerned:

- Patterns and architectures to support GDPR (for Europe) and PIPL (for China) regulations, such as isolated application deployments in these regions, annotation of privacy-sensitive information and domain models, etc.
- Increased usage of tooling for modelling such systems, including their (business) context, such as ArchiMate.
- Increased usage of Infrastructure as Code and Continuous Deployment tools to enable reliable and rapid continuous deployment of scalable cloud applications.
- Development of technology specific to working with vast amounts of timeseries data (such as TimescaleDB, InfluxDB, etc.).
- The use of X509 certificate based authentication / verification for IoT devices, in addition to their use in/between cloud services.
- Standardization of technology, processes and tools around secure firmware updates (e.g. Uptane, TUF).
- Combination of Artificial Intelligence with IoT (AIoT).
- Move of computational load to edge devices (Edge Computing).

3.9.3 Literature & academic research (low TRL)

Standards for security and safety challenges for Industry 4.0 are examined and new solutions are presented in V. Kharchenko et al. research [4]. The aim of this research is to enhance the conventional concepts of enterprise safety and security management by combining these two interrelated features in a single system.

Frey et al. [5] started from a real-world use case and derived a security perspective for an information-centric Industrial Internet of Things. They analysed the potentials of information-centric networking for providing a secure and robust networking solution for constrained controllers in industrial safety systems.

To improve the trustworthiness of an Industrial Internet-of-Things network, Hassan et al. [6] proposed a cyber-attack detection model, especially for detection of cyber-attack of Supervisory control and data acquisition (SCADA) by using the network traffics from SCADA based Industrial Internet-of-Things platform. This model uses industrial protocol-based network traffic.

Liu et al. [7] studied a network security and data redundancy of the Cyber Physical System in industrial environment and proposed a trust-based active detection (TBAD) scheme.

Bienhaus et al. [8] proposed a security architecture for a gateway connecting production systems, such as sensors and actors, with cloud systems. The security architecture in this work is based on a Trusted Platform Module (TPM) 2.0.

Blockchain is a promising technology that along with other enablers can significantly improve security, transparency and peer-to-peer interaction at a lower cost and with less energy. Lee et al. [9] propose a systematic blockchain based architecture to mitigate the inherent real-time implementation concerns of cyber physical systems in manufacturing application domain.

To simultaneously guarantee transaction efficiency and system security, Huang et al. [10] have proposed a credit-based proof-of-work (PoW) mechanism for IIoT devices. The proposed mechanism is based on directed acyclic graph (DAG)-structured blockchains which is further used to develop a data authority management method. This method regulates access to sensor data thereby protecting sensitive data confidentiality as well as data privacy.

The CHARIOT project [11] is developing an innovative design method and cognitive platform that supports a unified and integrated approach towards Data Privacy, Security and Safety of Industrial IoT Systems including several technologies.

Going beyond the state of the art, IMOCO4.E will take into consideration these approaches and will be an ideal solution for large-scale industrial deployments that require a high-level of security with minimal performance overheads.

Device and data security and secure communication for resource-constrained devices (e.g. https://www.ri.se/en/what-we-do/projects/sec4factory)

Application of blockchain technology in IoT to increase security (e.g. https://www.researchgate.net/publication/315854042_Managing_IoT_devices_using_blockchain_platform, https://www.mdpi.com/1424-8220/19/4/856)

3.9.4 Partner solutions (any TRL)

GNT & ITML	GNT will provide a data fusion mechanism that aggregates, pre-process, and further analyzes data from multiple different IoT sources in Industrial environments. Together with ITML will work on AI-based, real time data clustering and classification at the edge tool towards anomaly detection in data flows from IoT devices.
SIOUX	Sioux is involved in several cloud-based data analytics projects, with a wide variety of use-cases ranging from analyzing large datasets of a relatively small number of machines, to small datasets of many devices, and from near-real time processing of simple telemetry to running advanced machine learning algorithms.
OROLIA	Orolia will contribute to the integration of the AI-based Time Sensitive Networks (TSN) solution on IMOCO4.E framework.

3.9.5 Identified shortcomings

GNT:

GNT's data fusion mechanism has been tested with heterogeneous data sources (text, image, video, sound), and within the project, we will further increase the efficiency of the aggregation and pre-processing of the different types of data derived from multiple data sources increasing the fusion **speed by at least 20%.**

Together with ITML, we will increase the **accuracy (>95%)** of existing AI/ML algorithms for real-time data clustering and classification at the edge aiming towards more accurate anomaly detection in data flows from IoT devices.

Currently, the suggested solutions are developed for application in various domains (e.g. financial, transportation); within the scope of IMOCO we are planning to tailor the tools in the manufacturing sector, to be exploited towards predictive maintenance of complicated mechatronic systems.

SIOUX:

Partly due to the wide variety of use-cases, the architectures, tools, and technologies of these projects currently differ substantially. When setting up a new project, it is relatively hard to re-use previous architectures, knowledge, tools, etc. even though many of these projects clearly solve a similar set of problems, but appear to lack mutual compatibility and interoperability. In the end, there are so many new tools and technologies, standards, and regulations, etc. that it is hard to see the forest for the trees.

3.9.6 Potential IMOCO4.E progress beyond SotA

3.9.6.1 General

Apart from pure cybersecurity services based on AI algorithms to facilitate anomaly detection, this BB will be responsible to deliver a component which allows a trustworthy way of transferring data between the connected components and the permanent storage. We would like to converge to a common, cloud-agnostic reference architecture. It should provide a (very limited) set of options to adapt the architecture to the specific use-cases of each project. The definition of such a cloud-agnostic reference architecture for a common Equipment Management Platform as BB9 makes it easier to reduce the effort needed to 'bootstrap' new projects, while ensuring best practices around cybersecurity and data privacy are followed.

More specifically, solutions within BB9 concept will provide specific functionalities beyond the SotA as described in the table below.

Functionality	Baseline / State of the art (TRL 3)	Target (TRL 5), MS6 / M30
Intelligent anomaly detection mechanisms capturing cyber-threats real-time and at-the-edge with increased accuracy	ML-based anomaly detection carried out in a more centralized (cloud-based) manner	Deploy AI-based anomaly detection innovations at the edge
Real-time, trustworthy event and data management and relevant visualisations	Close to real-time, centralized event management systems	Ensure real-time event management
Efficient vulnerability assessment in complex Industrial IoT systems and in communication channels	Basic vulnerability assessment systems partially capturing complex IIoT environments	Thorough vulnerability assessment in IIoT environments

3.9.6.2 Related to Digital Twin

An important aspect of the reference architecture is a common data streaming pipeline, which can be used for connecting both digital twins and analytical processing and aggregation.

3.9.6.3 Related to AI and Data analytics

Within IMOCO4.E the potentials of AI/ML/DL technologies will be demonstrated in real-time data clustering and classification. More specifically and towards a trustworthy and secure dataset management and storage, a trustworthy data fusion technology will be deployed and be responsible for the aggregation and pre-processing of different types of data derived from multiple data sources, exploited towards predictive maintenance of complicated mechatronic systems. BB9 solutions will allow a trustworthy way of transferring data between the connected components and the permanent storage.

IMOCO4.E will exploit Kafka's various options for security, which include encryption of the data and client authentication and authorization, allowing only specific publishers and subscribers per topic. Data Replication over secure channels between the cluster nodes provides scalability, reliability and security. Elasticsearch[2] will also be exploited; data collected in the central Kafka broker is persisted in the Elasticsearch cluster.

3.9.7 Applicable standards, methods, tools

Tools that will be considered by the BB9 design:

- Apache Kafka [12] will be used for "building real-time streaming data pipelines that reliably get data between systems or applications" supporting multiple sources that can even be in a distributed system. As a message broker it offers higher fault tolerance in comparison to traditional message brokers and it can support significantly higher throughput. It is thus capable of handling great amounts of data and deliver them in real time to the components that require them. It can support multiple topics, which are used by producers and consumers of data to write and read data from respectively. A new topic can be easily created when needed in order to support the communication between new components or the new component can become a publisher or subscriber of an already existing topic. Multiple producers can write messages in the same topic and multiple subscribers can receive messages from the same topic. Subscribers can either compete for the same message, so that only one of them will receive it if they belong to the same group or they can all receive it if it is needed by multiple components. Apache Kafka offers various options for security as well, which include encryption of the data and client authentication and authorization, allowing only specific publishers and subscribers per topic. Within IMOCO4.E Kafka will be deployed in a cluster comprised of brokers located in the field gateways and a (central) broker in the cloud installation.

- Elasticsearch [13] is a distributed RESTful search engine built for the cloud. It resembles a NoSQL database being able to store data as JSON documents, but also works as a powerful search engine. Data is stored in the indices, which can be separated into shards and stored into a distributed system with replicas if needed. In contrast to traditional databases, the stored documents can have different format. Within IMOCO4.E data collected in the central Kafka broker is persisted in the Elasticsearch cluster. The Elasticsearch cluster can also be used by other IMOCO4.E components and BBs for querying historical data.

- Keycloak [14] is an open-source software product to allow single sign-on with Identity Management and Access Management aimed at modern applications and services. Within IMOCO4.E it can be used for securing access to the DFB Core and UI (and possibly to other components)

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3.10 BB10 Motion / path planning, collision avoidance and navigation algorithms

3.10.1 Market scan, COTS solutions (high TRL)

The increasing penetration of automated systems in intralogistics and production processes are responsible that related technologies becoming attractive for a widespread industrial marketing. Various solutions from well-known manufacturers are therefore offered on the market. As a rule, these systems are based on well-known sensor technology kits. Often a single sensor based environmental perception and motion planning is used. Usually, cameras, laser scanners or radar-based systems are used here. The high reliability and safety requirements for autonomous systems mean that most architectures in this area are quite similar.

What the autonomous mobile systems have in common is that, for the most part, they require not only powerful localization but also appropriate algorithms to determine the shortest path for economic processes in logistic areas. In localization, a distinction is made between local and global localization. Global localization is usually necessary to determine a starting point for the system. After that, the system can update its position during the movement via the local localization (mostly based on tracked and corrected odometry). If the localization is based on a map, the position can be determined using estimation methods and particle filters, such as Monte Carlo localization. If this is not available, SLAM (***Simultaneous Localization and Mapping***) mechanisms are used, which allow a map of the environment to be created during the orientation of the system. Since neither the map nor the position are known in this method, both must be estimated at the same time, which is correspondingly complex. Furthermore, there are camera-based systems that are mainly oriented to ceilings or floor markings and thus also allow a certain degree of localization.

Hardware

As already mentioned, autonomous mobile systems rely on sensor technology with a high TRL, due to the existing safety aspects in the regulations. Widely used are industrial approved 2D laser scanners that follow landmarks and shelf structures. This technology is also mostly used for collision avoidance. One of the benefits of the 2D laser Scanners is the high resolution what makes a very precise localisation possible. Another characteristic is the use of 3D laser scanners, which do not only scan in a defined level (with 2D lasers, this often makes it necessary to measure in 2 levels) but look at a larger area. However, the processing of the data is very complex due to the high data volumes.

If cameras are used, the choice varies from SW and RGB cameras to RGB-D or ToF (time of flight) cameras. As a rule, the specifics of the individual camera types are used to solve individual problems of the task.

Also used in this field are commercial radar sensors for industrial applications with multiple Tx-/Rx-channels which are available and applicable typically at these frequencies:

- Radar sensors at 24 GHz (ISM-Band, 250 MHz bandwidth)
  Examples (suppliers) for commercial solutions: Banner, InnoSent, NanoRadar, Radarxense, Symeo, …
- Radar sensors at 60 GHz (ISM-Band, up to 7 GHz bandwidth): Acconeer, Ainstein, Symeo, Colorado, Staal Technologies, NocellIC …
- Automotive radar sensors at 76-77 GHz and 77-81 GHz (frequency regulation to be verified for industrial use): Bosch, Continental, Smartmicro, Aptiv, Hella, InnoSent, Metawave, Oculii, Veoneer,

3.10.2 Emerging trends (rising TRL)

As already described at the beginning, most of the improvements relate to the expansion of the perception technologies that are used today. In addition, AI is being introduced in this area, to increase the efficiency of recognition and performance. In this case for example AI algorithms are supporting the implementation of analytics for complex radar signals (e.g., micro-Doppler evaluation). Also, Deep reinforcement learning is used for robot motion planning. In particular, the use of the imaging technologies described above is being promoted, as well as the use of 3D laser scanners, as they provide more information about the environment. All these projects support the more intelligent handling of obstacles, so that not only collision avoidance results, but also strategies are developed on how to deal with obstacles intelligently and, for example, to carry out agile path planning that takes all circumstances into account.

3.10.3 Literature & academic research (low TRL)

- 2006.14195.pdf (arxiv.org)
- Sensors | Free Full-Text | Autonomous Collision Avoidance Using MPC with LQR-Based Weight Transformation | HTML (mdpi.com)
- IEEE Xplore Full-Text PDF: (this is a nice one – but for cars)

3.10.4 Partner solutions (any TRL)

IMST starts with the "RoKoRa" radar (a result of a funded research project), which is a 77 GHz radar module with 3 Tx and 4 Rx channels with integrated signal processor board and USB or Ethernet interface (TRL = 5 at beginning of IMOCO4.E) This module will be adapted to fulfil the requirements of Demo 3 and to enable AI implementation and processing with additional signal processor.

STILL will contribute with results from the Deep-PTL and internal developments in the area of localisation, collision avoidance and path planing. This will base on the STILL intern iGo neo platform

3.10.5 Identified shortcomings

All in all, this is a very complex system in which shortcomings cannot be ruled out. The shortcomings, especially in the logical part, depend on the toolkits selected and the necessary interfaces, since many of them have a preference and are very specialized. Below some of them are listed.

- Radar antennas and frontend not suitable for Demo 3 (forklift application) -> new radar frontend with re-designed antenna
- Data interface(s) to be adapted to Demo 3, data formats to be defined with partners -> data interfaces and formats capable for obstacle detection, path planning and autonomous navigation in industrial environment
- Processor capabilities not useable for AI and neural network algorithms implementation -> new radar backend with AI processing capabilities
- Robustness against changing conditions / environments / uncertainties

3.10.6 Potential IMOCO4.E progress beyond SotA

3.10.6.1 General

In IMOCO, it is planned to include the whole area of intelligent environment analysis to create truly autonomous systems. This is not only a refinement of methods but also the integration of various other technologies to meet the following expectations:

- *Multi-sensory data input with sensor-fusion for extended environment detection*
- *Real-time decision making in path planning*

- *AI-based autonomy in unknown environments*
- *Using segmentation for path planning – the segmentation is coming from an AI model, within that segmentation we can create a view of a free space path planner*
- *Industrial radar sensor with AI capabilities for radar target classification*
- *Radar sensor for sensor fusion e.g. with video data*
- *Radar sensor development for Demo 3 but also applicable for pilots 4 and 5 (healthcare robotics and mining/tunnelling robotic boom manipulator)*

3.10.6.2 Related to Digital Twin

There will be extensive consideration of simulation aspects in BB10. This is only possible with a powerful data description. Models regarding a real store floor are currently not completely available. Aspects concerning the presence of people are rarely addressed at present. Here, extended analyses are planned. All these data models pay into the Digital Twin aspect.

3.10.6.3 Related to AI and Data analytics

As described above, AI and data analytics will play an important role. Certain solutions are inseparably linked to AI. The whole area of solution strategies and object recognition.

3.10.7 Applicable standards, methods, tools

No specific standards, methods or tools are existing

Know how from deep-ptl will be used by STILL as approved method (research project with successful output in this area).