

# OntoNav: A Semantic Indoor Navigation System

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## ABSTRACT

In this paper we discuss issues related to the underlying information infrastructure needed in order to support location services and routing in indoor environments. Location based services are typically encountered in outdoor environments and rely on Geographical Information Systems (GIS) in order to correlate a wealth of data to the present location of a mobile terminal. We discuss the very interesting issue of routing within a building environment. Existing approaches are based exclusively on geometric information and neglect important aspects like semantics bound to building areas and user profiles. Hence, the derived applications do not reach the intelligence level anticipated by modern users. We extend the existing approaches through the introduction of user profiles and the adoption of an ontological framework for handling routing requests. We discuss all the algorithmic background used by the proposed system for resolving this interesting problem of mobile information services.

## General Terms

Design, Algorithms, Human Factors.

## Keywords

Indoor navigation system, semantics, ontology, design for all

## 1. INTRODUCTION

During the last few years, the continuously increasing demand of individuals to be “*always connected*” and the technological advances in mobile devices and applications caused a boost in the penetration of wireless personal communications. This can be observed by the evolution of the 2nd and 3rd Generation mobile telecommunication networks, and also by the wide deployment of Wireless Local Area Networks (WLANs). These modern networks, in their turn, can facilitate the vision for ubiquitous services, which aid the users in their every-day life activities in an intelligent and unobtrusive way. This is actually an aspect of the ISTAG vision for “Ambient Intelligence” (more commonly known as Pervasive Computing paradigm) [4][7].

Another key enabler of pervasive computing apart from the ubiquitous networking infrastructure is the enrichment of the different systems with semantics (mainly through the definition of proper ontologies). Such semantically enriched system-

modeling aims at developing applications with enhanced functionality and advanced reasoning capabilities. Thus, pervasive computing environments can achieve the envisaged “Ambient Intelligence” by combining domain knowledge with advanced reasoning mechanisms, allowing the deployed services to explore hidden relationships between the system entities and to provide solutions to problems otherwise infeasible [8][9]. Currently, semantic technologies are mainly driven by the Semantic Web initiative and are used in a variety of application domains such as life sciences, automotive services, translation services, smart spaces and location based services (LBS).

In this paper we further investigate the aforementioned semantic LBS. More specifically, we present the design and development of OntoNav, an integrated navigation system for indoor environments, which is based on a hybrid modeling (i.e., both geometric and semantic) of such environments. OntoNav is purely user-centric in the sense that both the navigation paths and the guidelines that describe them are provided to the users depending on their physical and perceptual capabilities as well as their particular routing preferences. At this point, we should note that the “*physical capabilities*” include the user’s capability to walk, to see, to use stairs, etc. By the term “*perceptual capabilities*” we mean how easily one can be guided in an unknown environment. These latter capabilities depend usually on the user’s age and/or cognitive status. *Routing preferences* include user defined points of interest that should be included to the identified path, and preferences that rely on the semantic attributes of the path (e.g. fastest route, less demanding route, etc.). In fact, the system is mainly inspired by the widely adopted visions of Ambient Intelligence [7] and Design for All [6] (also known as Inclusive Design) and has been designed by taking into account people that have different limitations on way-finding and moving in indoor environments. However, the system can be extended to accommodate different virtual constraints (or preferences) of “normal” users. For example, a user who has no difficulty in moving around a building may want to plan its paths according to her/his scheduled tasks so as to be more productive and efficient. To better demonstrate our scheme’s innovation, let us consider the following usage scenario:

*Antony, an eight-years-old child with special needs who uses a wheelchair, arrives at its new school for the first time and he must immediately go to make a phone call. The child totally ignores the building’s topology but he is equipped with a PDA and, thus, accesses the Navigation Service offered by the school. Antony chooses as its navigation target the nearest telephone booth with support for wheel-chaired people. The system after a while presents him a route traversable by a wheelchair. In particular, it discards routes including stairs and seeks for routes either in the same floor or in another floor, which are accessible through ramps or elevators. The*

system uses user-friendly navigation instructions, taking into account the fact that the user is a child. Thus it presents the route through photographs of route key points instead of written instructions.

The organization of the paper is as follows. In Section 2, we review similar work. In Section 3, we discuss the overall architecture and functionality of the system. In Section 4, we define the key concepts of our navigation model and their classification in an Indoor Navigation Ontology (INO). We also describe, in detail, the user modeling and some indicative classification of user categories. In Section 5, we describe the geometric algorithms that are used for the determination of all possible paths, irrespectively of user capabilities. In Section 6, we discuss the reasoning tasks involved in the path selection, most of which involve ontological reasoning. The paper concludes with a short discussion and possible directions for future work.

## 2. RELATED WORK

As already mentioned, the primary goal of this work is the design and development of an integrated user-centric navigation system for indoor mobile environments. Until today, many works on outdoor pedestrian navigation systems have been proposed, which, in their majority, utilize Geographic Information Systems (GIS). The preference to the outdoor navigation systems can be merely attributed to the fact that there are better positioning infrastructures for outdoor environments [1]. Moreover, one could argue that indoor navigation is not as important as outdoor navigation, since built environments are more geographically constrained than their outdoor counterparts. Furthermore, even if one fails to discover a route towards his destination she can try again, without having spent (in general) much time and effort. These arguments generally hold true but not for cases of disabled people, elderly people or very extended environments such as hospitals where both the working staff and patients need to find and use the “best” traversable (accessible) navigation paths. The term “best” in the context of this work may occasionally refer to the shortest path, the easiest path (e.g., without stairs), the path that passes from many points of interest, the most popular from a set of possible paths, etc. In addition, the presentation of the selected paths is very important, as stated in the related bibliography [19] and should be also performed in a way inclusive of the user’s special characteristics.

In general, research on indoor navigation has not progressed significantly and is mainly motivated by robot navigation [2][3]. One of the first non-robot systems was the Cyberguide system [17], which was both an indoor and outdoor navigation system. It was designed as a tool for assisting tourists based on the knowledge of their position and orientation. The system displayed an arrow on a map whenever the user entered a new room. Infrared beacons determined the user’s position and her orientation was estimated from her actual walking direction and the topology of the building.

A similar system is the indoor component of the MARS system [14]. This component provides to visitors, students, and faculty staff information regarding the buildings of the Columbia university campus. MARS uses inference mechanisms and path planning to guide users towards their targets.

The Aura Location Identifier [13], part of Aura project at Carnegie Mellon University, uses a hybrid location model (semantic and geometric), which addresses the world as a hierarchy of spaces and levels with certain names, and with each

level further refining and subdividing the spaces of the previous level. Furthermore, different spaces may use different coordinate systems, allowing the system to define points or areas for which there is no name in the hierarchical name system.

However, the semantic modeling of navigation systems is still in its infancy. A quite interesting approach for spatial modeling with emphasis in navigation services is presented in [5]. We have borrowed the concept of exits from this work, since OntoNav navigates the users inside floors and buildings but it does not provide navigation instructions within rooms, although it could do so with some extensions. Other semantically enriched navigation systems are presented in [15][20]. PoLoS [22] is an enriched LBS platform for indoor/outdoor navigation, which aggregates both GIS information and user’s location for human navigational presentation purposes. An approach that is based on ontologies and the way humans navigate, select and mentally represent routes is the Navio project, described in [20]. Navio is aiming at developing a route modeling ontology which will provide both outdoor and indoor routing instructions to humans by identifying and formally defining the criteria, the actions and the reference objects used by pedestrians in their reasoning for routes.

To summarize, most systems, although they take into account the geographical coordinates of the navigation destination, they do not do the same with the user’s physical and perceptual capabilities as well as her routing preferences; in particular, they are using weights in order to compute the navigation path in the geographical – topological layer, based on the specific characteristics of the available positioning technology. On the other hand, OntoNav is a hybrid navigation system, since it transforms a problem of geographic path *determination* to a problem of both semantic and geographic path *selection* by utilizing ontologies and rules based on the physical and perceptual/cognitive characteristics of the users and on the semantic meta-information of the various path elements (passages, corridors, etc.).

## 3. ARCHITECTURE OVERVIEW

OntoNav is comprised of the following building blocks (see Figure 1):

**Navigation Service (NAV):** It is the main interface between the user and the system. It receives users’ requests for navigation and responds with the requested path (if any), in a form tailored to each user’s special characteristics (perceptual, physical and other preferences). The Navigation Service aggregates the Geometric Path Computation Service (GEO) and the Semantic Path Selection Service (SEM) and can also be interfaced, depending on the deployment configuration, with other systems such as user authentication or directory services and ontology repositories.

**Geometric Path Computation Service (GEO):** This service is responsible for the computation of all the geometrical paths from a user’s current location to a specified destination (Point of Interest, POI). Therefore, it utilizes a spatial database, where the building’s blueprints (ground plans) are stored. For the computation of the navigation paths the system executes a traditional graph-traversal algorithm on a graph representation of stored geometry. A graph creation algorithm, whose description is not in the scope of this paper, creates this path graph. The paths that are computed by the searching algorithm

are sent to the SEM Service for further filtering based on the user characteristics and routing preferences. The GEO Service is depicted in Figure 2 and is described in detail in Section 5.

**Semantic Path Selection Service (SEM):** This service provides the main functionality of our system and is responsible for the selection of the *best traversable* navigation path among those established by the GEO service. This path is one that matches all the capabilities and preferences of the user and it is, thus, selected based on predefined rules and on a user profile registry, which contains these user capabilities/preferences (see also Section 4.2). This task is achieved with the aid of a navigation ontology (see Section 4.1), which enables the required reasoning:

- path selection according to the physical capabilities and routing preferences of the user, and
- selection of the proper navigation guidelines (anchors), according to the physical and perceptual capabilities of the user.

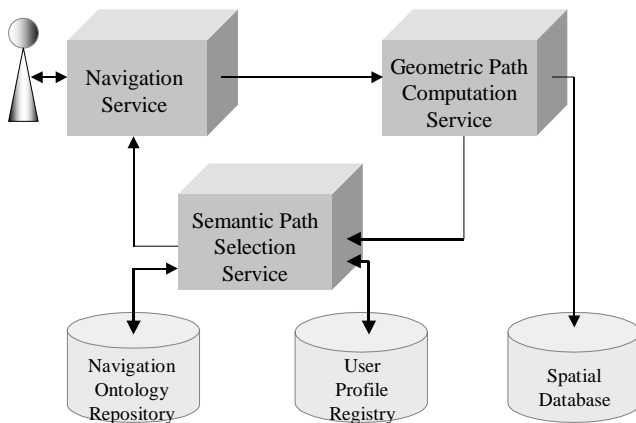


Figure 1. Overview of OntoNav Architecture

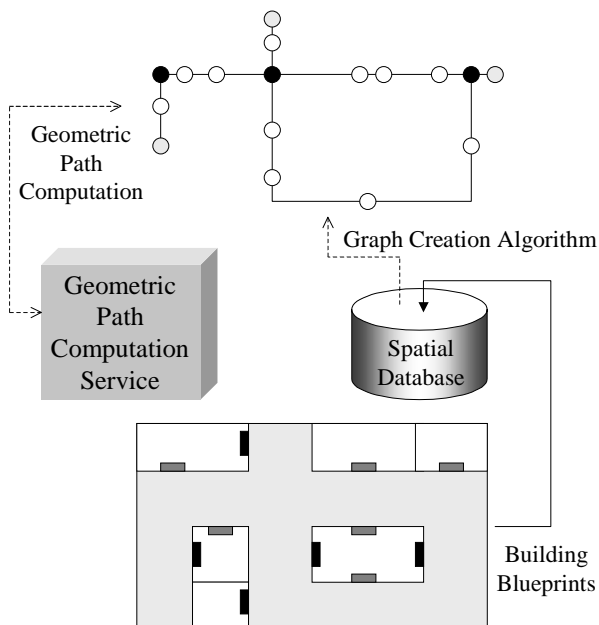


Figure 2. The GEO Service functionality

## 4. THE OntoNav SEMANTIC MODEL

### 4.1 The Indoor Navigation Ontology (INO)

The proposed navigation scheme is largely based on semantic descriptions of the constituent elements of navigation paths, which, in turn, enable reasoning functionality. Thus, we developed an Indoor Navigation Ontology (INO), which suits both the path searching and the presentation tasks of a navigation system. A core part of this ontology is depicted in Figure 3 (due to size limitations we do not present the complete ontology and the properties of the various classes – for a full version please refer to [24]).

A human-readable documentation of this ontology follows:

**User:** this concept represents the users of the navigation service, which have specific physical and perceptual capabilities/constraints. A (incomplete) classification of users is: blind, physically handicapped, children, elderly people and “normal” users. Additionally, a user could be classified according to her navigational status (e.g., deviated from a path, lost etc.).

**PointOfInterest:** any physical or virtual location or object, which may be of interest to a user (e.g., room, printer).

**Passage:** any spatial element that is part of a path and has specific accessibility properties. We can categorize passages to *horizontal* (connecting corridors in the same floor) and *vertical* (connecting corridors in different floors). The main types of vertical passages are elevators and stairs. The main types of horizontal passages are wheelchair ramps, doors, and crosspoints. Crosspoints are special types of passages that connect more than two corridors or enforce change of direction to users or indicate the start/end of corridors (e.g., a public open area - not room - leading to different corridors, a turn in a single corridor, etc.). At this point we should distinguish the term “door” from the term “exit”, described below. An exit is always attached to an indoor region (e.g., room), while doors connect corridors and/or passages and are always perpendicular to corridors.

**Exit:** an exit or entrance of an indoor region. Such region may be the whole building, a floor, or a room.

**Obstacle:** anything that prevents the passage of the user. That definition includes a) physical objects whose dimensions (width and height) block a corridor or passage, b) certain properties of exits or passages (e.g., closed door, non operating elevator), and c) other non-permanent conditions which prevent the passage of the user (e.g., security policies, a deluge of people in a space that makes difficult the passage of blind people, etc). The latter type of obstacles is very important as it enables the definition of dynamic and non-physical obstacles.

**CorridorSegment:** the concept of a corridor segment is a construct devised to facilitate modeling and it is derived by the geographic graph of paths (see Section 5). A CorridorSegment connects exits and/or passages.

**Corridor:** a corridor is comprised of corridor segments, which connect two crosspoints or a vertical passage and a crosspoint. A corridor can contain points of interest (POI) and obstacles.

**Anchor:** any passage, exit or POI included in a path that can aid the presentation of the navigation plan. Anchors cannot be movable objects. Examples of anchors are: crosspoints, doors, stairs and ramps. Thus anchors are mainly structural elements of buildings. However, non-structural POIs could also be used as anchors, e.g. a coffee machine.

**Path:** a sequence of interleaved corridors, exits and passages, which is capable of getting a user from its current location to a destination location. A *walkable path* is a special path, which can be used by any “normal” user. Apparently the set of

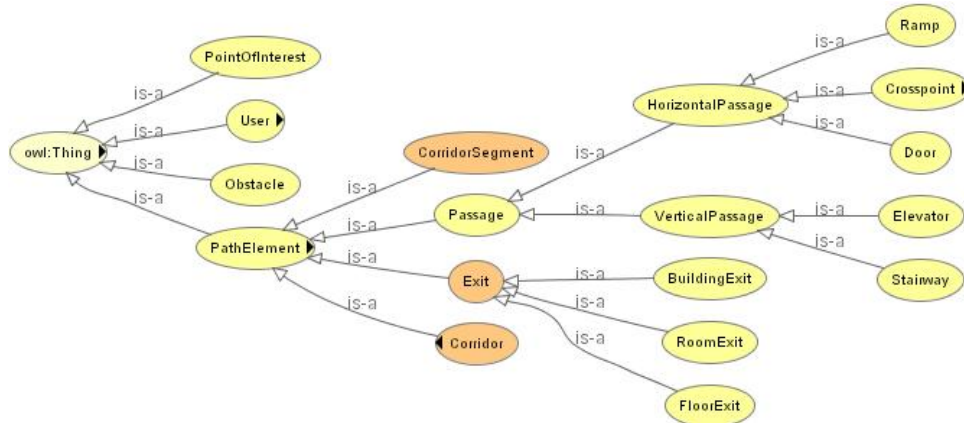


Figure 3. The Indoor Navigation Ontology

walkable paths in an indoor environment is the superset of all other path-sets, which are accessible by specific user classes. The geometric model (graph) of our system represents this superset (walkable paths). A path usually contains several POIs, anchors and obstacles. The subset of them, which will be used for the final user navigation, is defined depending on the user perceptual capabilities.

The aforementioned set of concepts cannot provide all the desired model expressiveness by itself. For that purpose we had to import elements of other spatial ontologies, which define spatial concepts and topological relations between them (e.g., we need the concepts *room*, *floor* and *building* in order to completely locate the POIs). We have developed a generic spatial ontology, which enables the description of generic indoor spatial environments and reasoning functionality on their *individuals*.

## 4.2 The User Modeling

The main objective of our system is to provide a user-centric navigation paradigm for indoor environments based on the user's physical and perceptual capabilities and limitations. In order to achieve this objective, the system is aware of the aforementioned user capabilities, which are described by the User Profile (UP). A UP is defined as a collection of classified attributes, most of which represent specific user capabilities/limitations. Such collection of attributes may be denoted as the set:

$$UP = \cup_i \{ \langle \text{attributeClass}, \text{attributeName}, \text{attributeValue} \rangle_i \},$$

for  $i=1..n$  different classes of grouped attributes. For the purposes of OntoNav we define three different and disjoint classes of attributes:

- The class of physical capabilities (i.e., attributes related to user's physical capabilities),
- The class of perceptual capabilities (i.e., attributes related to user's understanding of navigation guidelines),
- The class of preferences (i.e., attributes related to various user preferences regarding the path selection process)

Each UP instance is associated with a user. It is important to mention that it is this instance that is being used by the reasoning tasks described in Section 6. The first time a user invokes the system's interface, she creates her profile by providing all the indispensable information that can describe her physical and cognitive condition. Moreover, the UP is completely dynamic; the user may change her profile whenever necessary.

OntoNav uses the aforementioned user profiles in conjunction with various user-independent rules in order to infer which of

the walkable paths are suitable for a given user and how the navigation guidelines should be presented. These two selection processes are implemented with the aid of three kinds of navigation rules, the *physical navigation rules*, the *perceptual navigation rules*, and the *navigation preferences*, which correspond to the attribute classes of the UP set. The physical navigation rules are used for the selection of the paths that match the user's physical capabilities. The user, according to her UP profile, applies these rules to the set of all possible walkable paths in order to exclude those paths that are not traversable. The system determines that a path is traversable by a user if and only if it contains passages that can be used by her, does not contain any obstacles and matches her preferences. Some examples of the physical navigation rules are as follows (for size limitation reasons we will not refer to navigation preference rules):

- If *path p* contains an obstacle *o* then *path p* is excluded.
- If *user x* cannot walk and *path p1* contains a *vertical passage v* of type stairs then *path p1* is excluded.
- If *user u* can walk and carries an *object o* of a given width and the *path p* contains a *vertical passage v* of type elevator whose width is less than the width of *object o* then *path p* is excluded.

The perceptual navigation rules are rules that are used for the selection of the best-suited anchors across a traversable path for the best presentation of the navigation guidelines. The anchors are selected based on both the user's perceptual and physical capabilities. Some examples of such rules follow:

- If *user u* is a child (age less than 12 years old) and the *path p* contains an *element x* for which the system has visual/graphical descriptions then add *elements x* to the set of anchors.
- If *user u* is blind and *path p* contains an *element x* for which the system has auditory descriptions then add *element x* to the set of anchors.

## 5. THE OntoNav GEO SERVICE

The determination of the paths between two endpoints has been thoroughly studied in the literature [16]. Most related works model the navigation problem as a graph-searching problem. We also adopt this approach and use a graph for representing the different path elements of indoor environments. However, in such environments the existence of floors is an additional problem. In this paper, we present a graph model, which a) accumulates all the floor sub-graphs into one planar graph of the whole building and b) performs a

clustering algorithm for more efficient path discovery. The passages connecting two or more floors (i.e., stairs, elevators, ramps) are represented as single nodes in this graph.

Specifically, let us define a bi-directional, not fully connected, graph  $G_j$  for the  $j^{\text{th}}$  floor, with a set of vertices  $V_j$  and a set of edges  $E_j$ . A set of such graphs comprises the accumulated planar graph  $G$ , representing the path information of a building:

$G = \otimes_i (G_i)$  for  $i=1..#\text{floors}$  and the operator  $\otimes$  acts as a special concatenation of the floor sub-graphs. Thus,  $G = (V, E) = (\bigcup_{j=1}^n V_j, \bigcup_{j=1}^n E_j)$ , where  $n$  is the number of floors.

The set  $V_j$  is defined as follows:  $V_j = \{P \cup E\}$ , where  $P$  is the set of passages and  $E$  is the set of exits on the  $j^{\text{th}}$  floor (the notion of "exits" is borrowed from [5] and refers to room, floor and building exits/entrances). According to the INO taxonomy (see Figure 3), we can further specialize the set  $E$  by defining the subsets:

- RE (Room Exit): Such vertices are created by the vertical projection of each room exit to its adjacent corridor (see Figure 4).
- FE (Floor Exit): Such vertices denote the exits from one floor to another.
- MFE (Main Floor Exit): The set containing the main exit of each floor. An FE is a MFE if it satisfies some heuristic criteria, i.e. the most commonly used passage or the exit that connects the greatest number of floors. In the ground floor the MFE is also the main exit of the building.

Furthermore we can categorize the horizontal passages of type *crosspoint* to the sets:

- EP (End Point): These vertices denote the end of a corridor.
- J (Junction): The set of crosspoints, which connect three or more corridors.
- TP (Turn Point): The vertices of this set connect two corridors with (optionally) different directions.

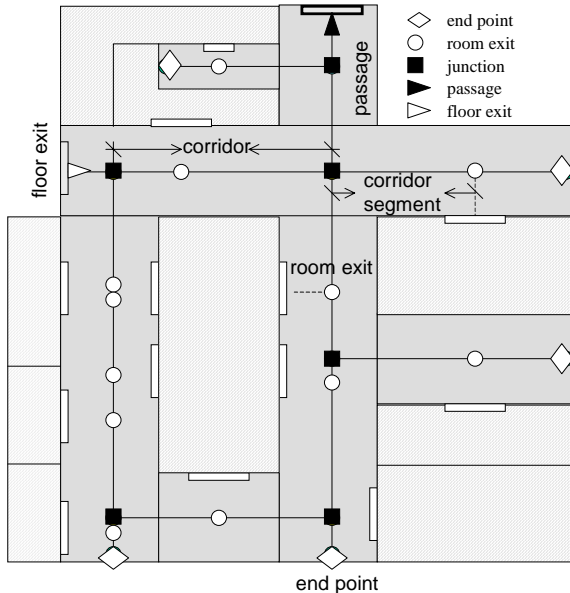


Figure 4. The path graph overlaid to the building's ground plan

The set  $E_j$  defines the edges (i.e. corridors) that connect vertices from the corresponding  $V_j$  set. The path graph  $G$  can be created by an appropriate algorithm, which takes as input the geometry

of the building's floor plans. This geometry can be built and stored in a spatial database (e.g., PostGIS [10]). The graph creation algorithm firstly creates a skeleton of the corridors (which are actually the edges) and then creates the vertices on this skeleton (by projecting the various spatial elements, such as exits, to the skeleton's line segments). During the graph creation we also calculate the lengths of the edges and assign a name to every vertex and edge. These names should be in correspondence with the names of the instances of the INO in order to enable further semantic reasoning on the paths.

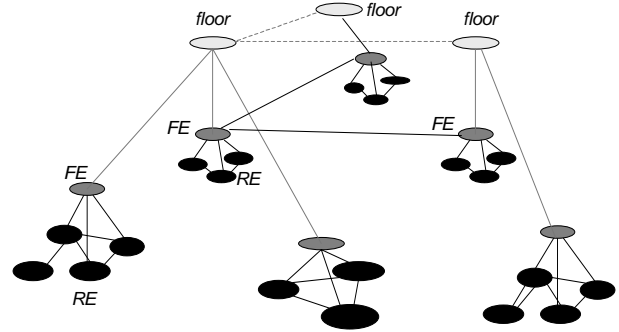


Figure 5. The Hierarchical Clustering Graph

```

Route (u,v)
//u:source, v:destination
T=∅
Begin
  f_u = floor(u) , f_v=floor(v)
  if (f_u=f_v) then S = interRouting(u,v) , T = T ∪ S
  else
    S_initFloor = interRouting(u,floor_exit(f_u))
    T = T ∪ S_initFloor
    S_j=∅
    for each floor j do
      begin
        S_j = S_j ∪ interRouting(main_floor_exit(f_j),floor_exit(f_j))
      end
      T = T ∪ S_j
    endElse
    S_termFloor = interRouting(floor_exit(f_v),v)
    T = T ∪ S_termFloor
  endElse
  Return T
End
interRouting(u,v)
// u:source, v:destination
S = ∅
Begin
  S = SearchGraph(u, v)
  Return S
End
floor_exit(f) : returns the FE that is closer to f
main_floor_exit (f) : returns the MFE of floor f

```

Figure 6. The Geometric Path Computation Algorithm

Subsequently to the creation of the graph we execute a graph-traversal algorithm in order to find the walkable paths between two given vertices. The output of this algorithm should be a set of one-dimensional vectors containing all the graph elements (edges and vertices) traversed by each walkable path. As the modelled buildings become bigger, their path graphs become larger and the sets of walkable paths increase in non-linearly fashion. To partly handle such computational complexity we perform clustering and create a *Hierarchical Clustering Graph* [11][12]. This is a tree-like

hierarchical graph with each cluster representing a floor graph (see Figure 5). The path computation algorithm (see Figure 6) first searches among the floors (the upper side of *the* hierarchy) and identifies which floors should be involved in the navigation. Then the algorithm is applied to the specific vertices of the graph of each selected floor (the lower level of the hierarchy). The various path segments computed between the floors and between the vertices of each floor are concatenated to form the final set of walkable paths.

## 6. MAIN REASONING TASKS OF OntoNav

In the previous sections we have described all the necessary modeling elements for an indoor navigation system. In this section we discuss how such elements can be combined into a reasoning process whose final outcome will be the selection of the best-suited navigation plan for the user that requested the Navigation Service. As already mentioned, this process comprises several reasoning and computational tasks. These tasks, described in the order of their execution, are:

### Task A: determination of the navigation starting point (S') and ending point (E').

We assume that S is the current location of the user, as determined by a symbolic indoor positioning system [18], and E the respective location of the requested POI. These locations are, in general, not represented as nodes in the graph. Thus, we need to match these locations with existing graph nodes (we should remind that the graph nodes can be either exits or passages of the considered environment). If we look more carefully to the problem, we see that S and E can be rooms, corridors or passages (users or POI can be located in such locations). Moreover, all these types of locations may have more than one exits or passages directly connected to them. In the first case (i.e., S and/or E are rooms) S' and/or E' are (in general) sets of exits. In the second case (i.e., S and/or E are corridors) S' and E' are sets of exits and passages. Finally, in the last case (S and/or E are passages), we can directly match the real points S and/or E to graph nodes representing passages, thus, S' and/or E' can be regarded as singletons. Thus, we have transformed our initial point-to-point navigation problem to a set-to-set navigation problem, between all the combinations of elements of sets S' and E'. These elements/nodes may not be the actual user or POI locations but are, in general, good approximations of them. Moreover, this approach enables the addition/removal of POIs without affecting the path graph topology.

### Task B: discovery of all the possible walkable paths that can lead the user from its current location S' to the target Point of Interest (location E').

This process determines (with traditional graph traversal algorithms) all the paths that a user can traverse for each combination of the S' and E' elements. If the set cardinalities are  $|S'|=s$  and  $|E'|=e$ , the complexity of the search algorithm will be  $O(se)$ . The output of this iterative computational task is a (possibly empty) set of walkable paths. For each walkable path its end-to-end length is also computed.

### Task C: semantic-driven selection of the Best Traversable Path (BTP).

This reasoning task is a two-phase procedure. During the first phase, reasoning is performed on the instances of the navigation ontology using the *physical navigation rules* and the *routing preferences*. In particular, such task uses these user-specific rules for the exclusion of the paths that are not traversable. A path is *traversable* if it supports the user's physical capabilities.

For example, the paths that contain stairs are excluded if the user uses a wheelchair. Thus, the first phase ensures that only the traversable paths are selected from the superset of walkable paths. In the second phase, which selects the *best* path, additional selection criteria are applied on this set of traversable paths. Such criteria are based on user preferences and may stipulate that the shortest traversable path should be selected, or alternatively the path that can serve the majority of the tasks described in the user's calendar. The output of this latter phase is a single path from the set of the traversable paths. While the first phase is default and predefined by our system, the second phase allows the adaptation of the path selection process to the actual *quality metrics* of the user. For example, the quality metric for a certain user can be the path length, while for another user, the scheduled tasks her/he can accomplish while traversing a navigation path.

### Task D: selection of the anchors across the best traversable path.

Anchors are the elements of the path that are best suited for the presentation of the navigation guidelines. During this process, all the anchors of the selected path are detected and are, then, matched against the *perceptual navigation rules* and the *physical navigation rules*. These rules define not only which anchors should be used, but also how many anchors should be used. As an example, assume that the navigation service requester is a blind man. In that case, we should choose *many* anchors with the requirement of having auditory descriptions. This reasoning task outputs a *sequence of navigation anchors* that are used, in turn, as input to the navigation presentation subsystem. The specific details of this latter subsystem are out of the scope of this paper, since we focus only on path modeling and path discovery/selection issues. The complete algorithm (in Java-like syntax), for the selection of the Best Traversable Path (BTP) for a specific user and of the corresponding anchors for the navigation guidelines, is depicted in Figure 7.

```

userProfile = getProfile(userID);
int numOfPaths = 0;
walkablePaths = findAllWalkablePaths(userLocation,
                                       POILocation);
for (i=0; i<walkablePaths.length; i++){
  for (j=0; j<walkablePaths[i].length; j++){
    pathElement = walkablePaths[i][j];
    if (pathElement == passage &&
        pathElement.isTraversable(userProfile.physicalRules)
        if (j==walkablePaths[i].length-1){
          //if all passages were traversable then
          //add the path to the selected paths matrix
          selectedPaths[numOfPaths]=i;
          numOfPaths++;
        }
      }
    else continue;
  }
}
if (numOfPaths == 0)
  return null;
else if (numOfPaths == 1)
  BTP=selectedPaths[0];
else BTP=shortestPath(selectedPaths);
BTPAnchors=BTP.findBestAnchors(UProf.physicalRules,
                                UProf.physicalRules);

```

Figure 7. The method names written in italics correspond to the reasoning tasks described earlier as tasks A-D.

## 7. DISCUSSION

In this section we reason about the added value that OntoNav provides to users, and discuss some deficiencies identified in its current design.

Psychologists have proven that navigation is a highly demanding process, which requires various cognitive abilities in order to let a person to fulfill successfully fulfill a navigation task. This is especially valid for large and complex built environments, which, in general, do not provide their tenants and guests with all the information required to perform an optimal route choice. Weisman [23] identified four classes of environmental variables that influence the navigation performance within a complex built environment: visual access, the degree of architectural differentiation, the use of signs to provide identification or directional information, and plan configuration. The overall navigation performance of a human can be further influenced by her physical, mental or cognitive status.

OntoNav is an approach to deal with this problem in a user-friendly way. The proposed navigation system is user centric in the sense that not only the navigation paths are calculated and selected with respect to the user's capabilities and routing preferences but also the routing instructions and guidelines are personalized and tailored to the user's perceptual capabilities (not described in this paper).

Until now, most approaches of indoor navigation typically consider buildings as flat, 2-dimensional spaces in which they identify optimal (shortest) paths, by calculating Euclidean distance. OntoNav, by having a complete, navigation ontology of geometrical space and user characteristics, adopts a richer notion of distance. The use of ontology for modeling allows the determination and calculation of novel navigation costs (by utilizing ontology's advanced reasoning capabilities). Furthermore, OntoNav is context-aware and adaptive to dynamic changes of either the environment or the users' characteristics/preferences.

However, despite the advantages that the semantic modeling provides, there are still some issues that could constitute potential problems and, therefore, should be addressed. The major deficiency of the presented system is probably the high computational cost of the greedy graph traversal. We remind that the GEO service computes all the walkable paths in contrast to other approaches that use shortest path algorithms (e.g., A-star). However such greedy computation of paths is inevitable as the shortest paths may not be accessible by all users. Another inevitable performance handicap is the execution of the graph traversal algorithm not on a point-to-point basis but on a set-to-set (see Section 5). The reason for that "complexity explosion" is, again, the fact that for special types of users only a few traversable paths may exist and, in general, they may not be the shortest ones. One way to overcome this deficiency is to abandon the graph creation and the geometric path computation and merge the tasks B and C with the aid of rules applied directly on the ontology instances. In fact, the main reason for using a graph is that we can derive *ordered sets of path elements* with a common graph traversal algorithm. We currently study the possibility of performing the path selection while discovering the possible next-step path elements.

Another way to minimize the computational overhead would be the caching of already computed paths. We could cache whole paths that were successfully computed in the past. Relying on a cached path, however, may be risky as the path traversing properties can vary over time (e.g., an elevator may be out of

order, while in the previous day it was operating). This risk is bigger for disabled people, who may spend significant effort in navigating. Thus, we may first check the condition of a cached path and only if it is not suitable, then perform the entire described above procedure. However, this caching scheme may not affect significantly the system performance, since some paths are requested rarely. For example, a path request from the main exit of a museum to exhibit A is much more probable than a request from an exhibit, B, to exhibit A. That is, because the visitor flow through the main exit is much greater than that through exhibit B, or, in other words, the main exit serves more potential path requestors. For that purpose, it seems reasonable to cache only the most frequently requested path segments. By computing various statistical measures, while performing the aforementioned path selection tasks, one can estimate the set of such segments. Furthermore, constructing query patterns or path patterns of a user could reduce computational complexity since the graph has been modeled into a hierarchical clustering scheme. Such scheme facilitates the pattern extraction process since we focus on higher layers of the hierarchical graph. Once we have selected the traversable path requested by a user, we have to take into account the presentation of such path to the user. A *semantic* filter of the user's profile and preferences and the contextual information residing into the spatial database produces the path selection.

Another challenge we faced is the generic modeling of space and paths. Such modeling seems to be very difficult (if feasible) due to the high complexity and variety of building elements. In fact such modeling is heavily dependent on the architectural constructs, which are not constant and strictly specified. We believe that every ontology aiming to model built environments should have extension points, catering for possible future adaptations and extensions.

Finally, for completeness reasons, we mention that two more challenges for indoor navigation are the development of automated feature extraction methods for the storage of building blueprints to spatial databases, and the improvement on the accuracy of the indoor positioning systems.

## 8. FUTURE WORK

The issues reported in Section 7 are highlighting some of our future work. Furthermore, our research will be focused on the implementation of a navigation assistance module (NAM). The system described so far, computes routes between an origin and a destination point in a static manner. That means that after the path calculation and the provision of the routing instructions to the user, the system does not assume any further actions. While this functionality may be satisfactory for a great amount of users, there are some user categories, such as children or adults with visual impairments, for which it is easier to deviate from the planned navigation path. Thus a reactive navigation aiding service with main task to detect deviations from the calculated path and to provide guidelines for relocation to the initially planned path is required.

In this paper, we have described a semantic indoor navigation system. OntoNav is currently in its development phase. When the implementation is complete, we aim to evaluate its effectiveness and performance through its real-world deployment in the facilities of our University Campus.

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