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Semantically enriched navigation for indoor environments

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Abstract: Location-based mobile services have been in use, and studied, for a long time. With the proliferation of wireless networking technologies, users are mostly interested in advanced services that render the surrounding environment (*i.e.*, the building) highly intelligent and significantly facilitate their activities. In this paper our focus is on indoor navigation, one of the most important location services. Existing approaches for indoor navigation are driven by geometric information and neglect important aspects, such as the semantics of space and user capabilities and context. The derived applications are not intelligent enough to catalytically contribute to the pervasive computing vision. In this paper, a novel navigation mechanism is introduced. Such navigation scheme is enriched with user profiles and the adoption of an ontological framework. These enhancements introduce a series of technical challenges that are extensively discussed throughout the paper.

Keywords: indoor navigation; Semantic Web; ontology; user models; universal access; path selection; shortest paths.

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1 Introduction

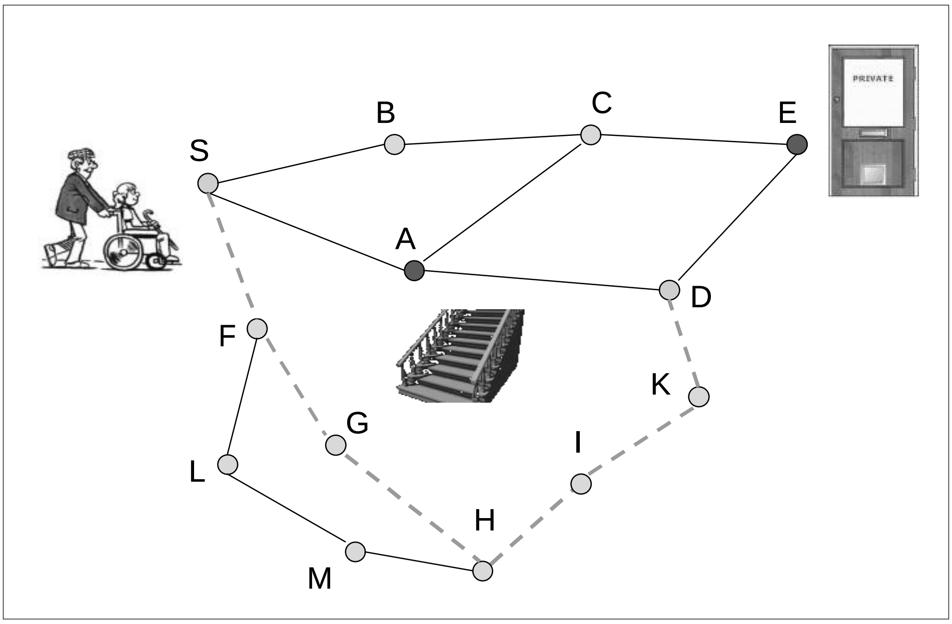
During the last few years, the continuously increasing demand of individuals to be *always connected* and the technological advances in mobile devices and applications caused a boost in the penetration of wireless personal communications. This can be observed by the evolution of the 2G and 3G mobile telecommunication networks, and also by the wide deployment of Wireless Local Area Networks (WLANs). Such networking technologies, in turn, can facilitate the vision for ubiquitous services, which assist the users in their everyday activities in an intelligent and unobtrusive way. This is an aspect of the ISTAG vision for 'Ambient Intelligence' (also known as the Pervasive Computing paradigm) (Satyanarayanan, 2001; ISTAG, 2001).

Another key enabler of pervasive computing applications, apart from the ubiquitous networking infrastructure, is the enrichment of the applications with semantics. This is mainly achieved through the definition of proper ontologies. Ontology (Gomez-Perez *et al.*, 2004) is the most popular and practical technology for representing models. Ontology is defined as "an explicit and formal specification of a shared conceptualization" [Gruber]. In other words, it is a method for describing models of application domains that can be understood by machines. Such semantically enriched system-modelling aims at developing applications with enhanced functionality and advanced reasoning capabilities. Hence, pervasive computing environments can achieve the envisaged 'Ambient Intelligence' by combining domain knowledge with advanced reasoning mechanisms. This way, they allow the deployed services to explore hidden relationships between the system entities and provide solutions to otherwise infeasible problems (Chen and Finin, 2003; Ranganathan *et al.*, 2003). 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 issue of semantic LBS. Specifically, we discuss the design and development of OntoNav, an integrated indoor navigation system, which is based on a hybrid modelling (*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, subject to 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 the stairs, *etc.* By the broader term *perceptual capabilities*, we mean how easily one can be guided within an unknown environment. The latter capabilities usually depend on the user's age and/or cognitive status. *Routing preferences* include user-defined points of interest that should be included in the identified path, and preferences that rely on the semantic attributes of the path (*e.g.*, fastest route, less effort-demanding route, *etc.*). The system design is mainly inspired by the widely adopted visions of Ambient Intelligence and Design for All (European Institute for Design and Disability, 2005) (also known as Inclusive Design) and has been designed by taking into account people that have different limitations on wayfinding and moving in indoor environments. To better demonstrate the motivation behind our system, let us consider the following usage scenario (Figure 1), which illustrates how much difficult indoor wayfinding may become (similar difficulties may occur for other categories of users, such as the blind and elderly):

Anthony, a person who uses a wheelchair, wishes to reach destination D from his current position S, inside a large and complex building. The graph in the figure is a logical (not geographic) representation of the building topology, where edges and vertices represent corridors and passages (*e.g.*, stairs, elevators, doors). In addition, the lengths of the edges represent the respective distances. Should Anthony follow the path {S,A,D}, which is the shortest one, he will have to eventually return back to S, since there is a stairway at A. If he chooses to follow one of the paths starting with {S,B,C} he will, again, come to a dead-end, since there is also a door at E, which leads to a restricted-access area. Hence, he has to return to S again and choose a path towards the direction of F. To sum up, in a worst case scenario, Anthony may follow a path like {S,A,S,B,C,E,C,B,S} before he finds a path that can lead him to his desired destination, D.

Figure 1 Use case of indoor navigation



Notes: A: stairs, E: restricted-access area

The paper is organised as follows. In Section 2, we review related work in navigation systems, in general, and in specific subsystems and components involved in them. In Section 3, we discuss the overall architecture and functionality of the system. In Section 4, we define the key conceptual entities of our navigation system and their representation through Semantic Web ontologies and rules. Such entities are the spatial building model, the user model and the path selection rules. In Section 5, we elaborate on the implementation technologies and provide an evaluation of the system performance. The paper concludes with a short discussion on possible directions for future work.

2 Related work

LBS enable location-aware content provision. Apparently, a key enabler of LBS is the positioning infrastructure. As far as outdoor environments are concerned, the most widely used positioning method is the Global Positioning System (GPS), which provides spatial information with high accuracy and availability at low cost. On the other hand, there exist many alternative positioning solutions for indoor spaces, but none of them have been standardised yet. Such solutions include WLAN triangulation, dead-reckoning techniques (implemented with accelerometers and digital compasses), Radio Frequency

Identification (RFID) tags, and infrared/ultrasound beacons. Hightower and Borriello (2001) provide an extensive survey of indoor positioning techniques. A basic assumption for developing our system is that we have secured access to an indoor positioning system. Such system can locate users with 'adequate' accuracy.

Former indoor navigation research focused on robot navigation. As the positioning systems have matured, more effort has been placed on developing indoor navigation services for pedestrians, such as museum guides aiding the sightseeing of tourists. An indicative system in this category is CyberGuide (Abowd *et al.*, 1997). Another, more recent and more sophisticated, navigation system is Navio (Gartner *et al.*, 2004). Navio aims at developing a route modelling ontology, which provides both outdoor and indoor routing instructions to humans. This is performed by identifying and formally defining the criteria, the actions and the reference objects used by pedestrians during navigation. However, Navio research emphasises on location fusion (*i.e.*, the aggregation of location information from multiple sensing elements) and user interfaces, and thus, does not contribute significantly to the issue of path selection. This latter issue is of utmost importance for human-centred LBS, but is often overlooked or oversimplified. In general, the majority of existing systems focus on the path presentation to users and on the hardware/positioning infrastructure used.

Additionally, some systems have been developed for addressing the special needs of certain user categories, *e.g.*, navigation for blind people. Such systems, however, lack a holistic approach to the navigation process. Their internal mechanisms are not generic enough to address the whole range of potential application requirements. This drawback of existing solutions, as well as their deficiencies that will be identified in the following subsections, have motivated the present research in user- and space-modelling, path selection and navigation algorithms.

2.1 Path-searching algorithms

Since navigation is a path-searching algorithmic problem, the decision on the *path-searching* algorithm used is vital for the quality of the provided service. Most of the existing navigation systems, either indoor or outdoor, adopt *conventional* shortest path algorithms (*e.g.*, Dijkstra, A-star), thus, recognising the minimisation of Euclidian distance as the only objective in the path selection process. However, such approach overlooks the significance of other objectives that are more relevant to the context of the user. Hence, significant research on that topic has identified that pedestrian navigation needs more sophisticated and human-centred path-searching algorithms. Duckham and Kulik (2003) have proposed the 'simplest path algorithm'. In this algorithm, the selected path is the one with the lowest possible complexity in navigation instructions. This work belongs to the category of approaches that introduce modifications of well-known graph-routing algorithms, such as the aforementioned shortest path algorithms. A rather similar approach is discussed in (Grum, 2005), where the proposed navigation algorithm computes the 'least risk path'. The term 'risk' refers to the possibility of disorientating the user.

The aforementioned algorithms, although providing more 'intuitively correct' paths than the conventional shortest paths algorithms, do not take into consideration the user semantics, as dictated by the modern 'design for all' paradigm. This paradigm promotes the design and implementation of services and products so that they can be used by any user, without any further adaptation. The implementation of such a paradigm, in the LBS domain, would lead to services that can be used (in an optimal way) by any user, regardless of his/her special characteristics.

2.2 *Spatial models, user models and ontologies*

The quality of *path-searching* algorithms also depends on the spatial modelling of the navigation space. Many approaches with different data representations and expressiveness have been proposed for spatial modelling. Specifically, *geometric* models represent the navigation space using a certain coordinate system and mainly support geometric queries (*e.g.*, where is the nearest coffee machine?). On the other hand, *symbolic* models represent the navigation space through sets of symbols (*i.e.*, names) and inter-symbol relationships, capturing the topological semantics (*e.g.*, 'part-of' and 'overlaps' spatial relations). Finally, *hybrid* models are combinations of the former two categories, aiming at maximising the expressiveness of the spatial model. An interesting comparison of spatial models is presented in Leonhardt (1998). As far as indoor navigation is concerned, only a few researchers have proposed practical, yet expressive, models. In our view, the most important one is presented in Hu and Lee (2004). It is a hybrid model, which represents the space as semantic hierarchies of 'locations' and 'exits' that also carry geometric information (*e.g.*, coordinates).

The use of semantic spatial models results in what has been called 'Semantic Location-based Services'. However, we claim that actual semantic LBS should not only exploit semantically enriched spatial models (symbolic or hybrid), but also take into consideration the *navigation context* (*i.e.*, user context and instantiation of spatial model). Hence, we propose a refinement of the term 'Semantic LBS', or better 'human-centred LBS', so that it supports the following requirements:

- awareness of spatial semantics (*e.g.*, hybrid model)
- awareness of navigation context
- adherence to the design-for-all paradigm
- reaction to dynamic user or space status changes.

As will be discussed in the following sections, such services can be built with a knowledge-based system architecture. This architecture exploits knowledge representation methods to model the various components and reasoning/inference techniques, in order to implement the actual path selection process. Knowledge reasoning is the process of inferring new knowledge from explicit knowledge assertions. Such reasoning can be based either on logic-based methods (*i.e.*, resolution) or production rules (Brachman and Levesque, 2004).

2.3 *User modelling*

Because navigation and wayfinding are two demanding mental procedures, especially for people with disabilities (visual, mental, sensory, *etc.*), one may adopt a number of approaches for providing universal access to navigation services (Gluck, 1990; Downs and Stea, 1973; Allen, 1999; Timpf *et al.*, 1992). The majority of such approaches share a common characteristic – they support a single or a limited number of static user profiles, *i.e.*, with predefined user characteristics. In most cases, the user of the system can only slightly modify the profiles. Even if there are some cases where more detailed user profiles exist (Siegel and White, 1975), their main usage focuses on the personalisation of the system's presentation modality (*e.g.*, map drawing, voice dialogues, *etc.*).

To the best of our knowledge, there is no other user model for describing user characteristics from the perspective of navigation. Of course, there are some generic user modelling efforts that try to cover a wide range of application domains and adopt open technologies for enabling system interoperability. The most relevant work of this category is the General User Model Ontology (GUMO) (Heckmann *et al.*, 2005). GUMO is implemented in OWL (Web Ontology Language), a popular language in the Semantic Web (Berners-Lee *et al.*, 2001) community not only for its ability to provide a well-defined syntax for modelling purposes, but also for its capacity to extensively describe the implicit semantics of a domain model. GUMO has means of representing several 'user dimensions', such as demographics, abilities, emotional and psychological status, *etc.* In addition, it supports the specification of some supplementary information, such as the preferences, interests and knowledge of the users. The OntoNav user model (see Section 4.2) is, to a certain degree, aligned with GUMO by reusing and extending some concepts and attributes. GUMO has been partially influenced by the UserML language (Heckmann and Krüger, 2003). UserML's objective was to provide a commonly accepted XML-based syntax for representing user models in web applications. UserML is quite generic and can thus be used only as a syntax layer for more advanced semantic user models.

3 System architecture and functionality

In this paper, we propose a framework for human-centred semantic indoor navigation, which meets the requirements presented in previous sections. Such framework, named *OntoNav*, is based on a novel combination of ontology-based knowledge representation and reasoning technologies, as well as path-searching algorithms. The architecture of the implemented navigation system is illustrated in Figure 2 and can be decomposed into the following basic components:

- Navigation service

  This service can be defined as the interface between the system and its users. It accepts navigation requests and responds with the optimal path, if any. Path optimality depends on several factors, such as the suitability for current user context and length of the selected paths.

- Indoor navigation ontology

  This spatial ontology, named Indoor Navigation Ontology (INO), describes the basic spatial and structural concepts of indoor environments, as well as their relationships. Specifically, it provides a semantic spatial model for reasoning about the selected paths. More details on INO are provided in Section 4.1.

- User navigation ontology

  In order to model user context (*e.g.*, profile, abilities, constraints and preferences), we have developed an ontology named User Navigation Ontology (UNO). This ontology contains user classes and elements of the user context. Hence, each user profile is classified into one or more navigation classes according to his/her characteristics. Possible user classes are: HandicappedUser (*i.e.*, person who cannot walk), BlindUser (*i.e.*, person who cannot see), LazyUser (*i.e.*, person who always prefers elevators to stairs or is in a hurry), to cite a few. Both the INO and UNO ontologies have been modelled through OWL (McGuinness and Harmelen, 2004). More details on UNO are provided in Section 4.2.

- Path selection rules

  The path selection process is performed through a set of rules. The definition of such rules also involves the spatial semantics (*i.e.*, spatial relationships expressed through the INO ontology) and the user semantics (*i.e.*, user preferences/profile expressed through the UNO ontology). The rules are applied to the INO instances in order to determine the paths that are considered appropriate and accessible for each user request. More details on the role of rules in OntoNav are provided in Section 4.3.

- Indoor geospatial model

  The INO instances are created through a geometric representation of the indoor topology. Such geometric data may initially reside in a Geographic Information System (GIS) as building blueprints and be, subsequently, transformed to actual spatial ontology instances. In the rest of this paper, we assume that the INO instances have been created beforehand and thus, do not delve into the details of such creation process.

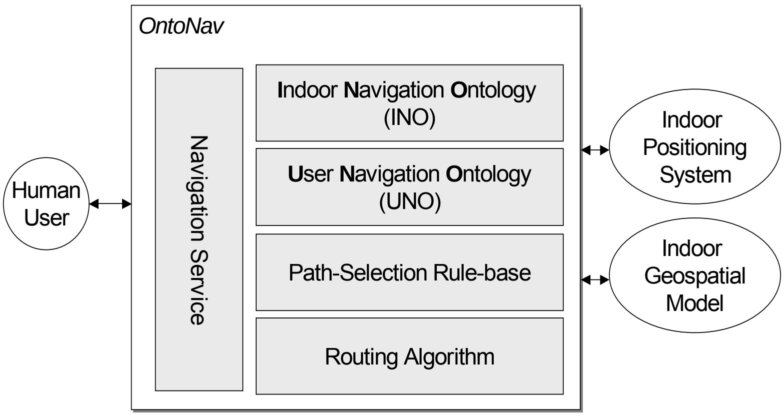
- Routing algorithm

  This algorithm is a central element of the framework and, in combination with the Path Selection Rules, is responsible for the determination of the optimal path between two given endpoints. The algorithm used in OntoNav is a *k-shortest paths searching algorithm*. Similar to the approach in Wu and Hartley (2004), such algorithm facilitates more flexible path selection by enabling the inclusion of additional restrictions imposed by the user context. The main idea is that the shortest path may not always be the optimal path. Hence, we compute k shortest paths, so as to be able to choose the optimum path (*i.e.*, the shortest path that satisfies the user restrictions). More details on the adopted algorithm can be found in Yen (1971).

- Indoor positioning system

  OntoNav symbolically locates the users in the navigation space according to the spatial model described by INO. The positioning infrastructure may vary from infrared/ultrasound beacons to WLAN triangulation or dead-reckoning techniques. It is important to note that, in cases where the positioning accuracy is better than the location modelling granularity, an approximation error may be introduced in the estimated location of the user. However, this error does not significantly affect the quality of navigation.

Figure 2 OntoNav architecture



3.1 Description of system workflow

The end-to-end functionality of the system is depicted by means of flowcharts in Figures 3 to 5. Figure 3 depicts the system initialisation process, in which the spatial ontology instances are loaded. Figure 4 illustrates the workflow that takes place upon a navigation request from a user. Initially, the user registers his/her profile to the system, and the destination he/she wishes to reach. His/Her current location is determined through the Indoor Positioning System. If the user has not registered to the system again, then his/her profile is instantiated in the UNO ontology and a new Navigation Service instance is created. Such instance mainly consists of the topology graph associated with the specific user. It should be noted that this graph is created from the INO instances, after the application of the physical navigation rules described in Section 4.3. Such rules identify all the path elements that are accessible by that specific user. Such graph is the basic input to the next task, as illustrated in Figure 4, where the *k-shortest paths* between the user and the destination location are computed. Subsequently, for each path, a total *quality score* is calculated, denoting the degree to which a path satisfies the perceptual navigation rules and preferences. The path with the highest score is the one proposed to the user.

Figure 3 System initialisation

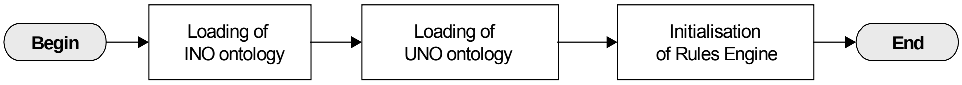


Figure 4 System workflow after a user navigation request has been received

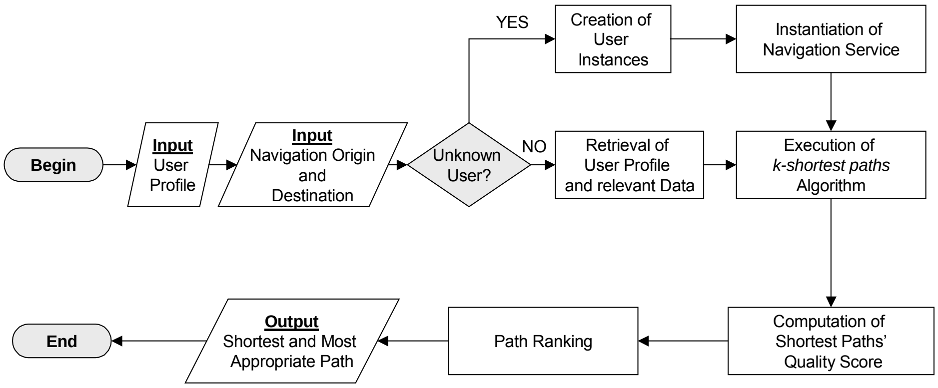
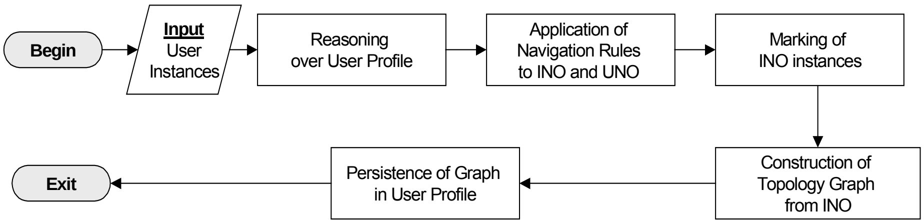


Figure 5 The workflow for the creation of a new navigation service instance

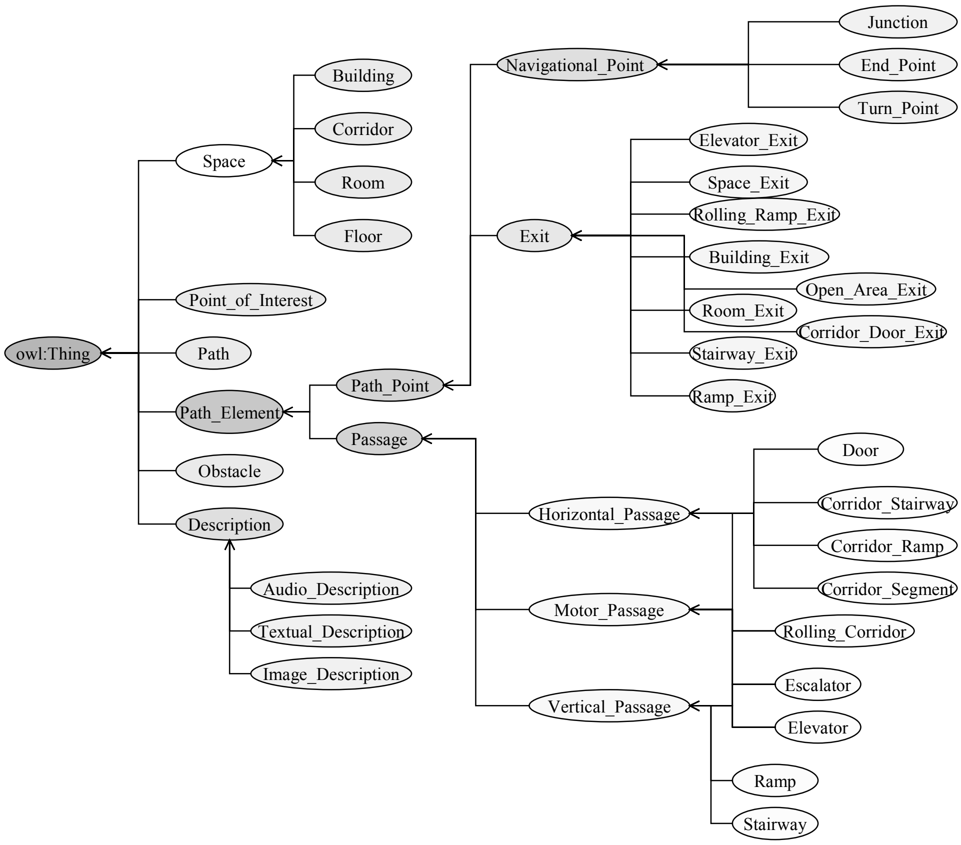


In Figure 5, one can see that the UNO instances (*i.e.*, user profile) are the main inputs to that task. Those instances pass through a reasoning engine, which classifies the user with respect to the defined UNO classes. Subsequently, all types of rules are applied to the INO and UNO knowledge bases. Specifically, the physical navigation rules 'mark' the INO instances for further exclusion from the process, whilst the perceptual navigation rules and navigation preferences reward or penalise certain INO instances pertaining to the specific user. The unmarked elements are used for the creation of the user-accessible topology graph, which is also stored in the user profile for future use.

4 Spatial modelling with the indoor navigation ontology

The proposed navigation scheme is largely based on semantic descriptions of the constituent elements of navigation paths, which, in turn, enable reasoning. Hence, we developed an INO, which supports both the path-searching and presentation tasks of a navigation system. The basic taxonomy of this ontology is depicted in Figure 6. The INO, apart from concepts, also includes roles (binary relationships between concepts, a.k.a. properties), axioms and constraints (a.k.a. restrictions) on these roles.

Figure 6 The indoor navigation ontology



INO has three basic concepts, *Path_Element*, *Description* and *Point_of_Interest*, that represent physical spaces and navigational elements, their descriptions and possible navigation destinations, respectively. Such concepts are interrelated through well-defined ontological roles in order to model a design space available for semantics-driven pedestrian navigation. An explanation of the main INO concepts follows:

- Path_Element – this concept models the physical or conceptual elements of a navigation path. It subsumes (*i.e.*, aggregates) the physical passages as members of the *Passage* concept and their conceptual representations as members of the *Path_Point* concept.
- Passage – this concept is any spatial element that is part of a path and has specific accessibility properties. We further classify passages to *Horizontal* (*i.e.*, connecting corridors in the same floor), *Vertical* (*i.e.*, connecting corridors in different floors) and *Motor,* which are horizontal or vertical passages that are motor-powered. The main types of vertical passages are elevators and escalators and the main types of horizontal passages are ramps and doors. At this point, we should distinguish the class *Door* from the class *Exit*, described below. An *exit* is a logical representation of

an indoor region or passage (*i.e.*, a passage instance is represented by one or more *Exits*), while doors connect rooms and corridors, or corridors to other corridors (thus, being perpendicular to them).

- Path_Point – this concept models the logical representations of physical passages through a point-based abstraction, suitable for further transformation to a path graph model. There are two types of *Path_Points*: *Navigational_Points* and *Exits*.
- Navigational_Point – special points that connect more than two corridors (*i.e.*, junction points) or enforce a change of direction to users (*i.e.*, turn points) or indicate the end of corridors (*i.e.*, end points).
- Exit – an exit or entrance of an indoor region or passage. Such region may be the whole building, a room, an elevator, *etc.* This concept is borrowed from Hu and Lee (2004) and each indoor region and passage is represented by a set of exits.
- Space_Exit – this specific concept (subconcept of *Exit*) denotes a virtual point in the the interior of an area (*i.e.*, room) that is directly connected to the set of *Exit* individuals (*i.e.*, instances) that lead to this area. This concept is used whenever the target and/or destination of the navigation are physically located inside rooms.
- Description – this concept models multimedia information (*e.g.*, audio, image and textual descriptions) that characterises a physical passage or point of interest in the physical space. This characterisation is used for graphical, textual or oral instructions during user guidance according to user profile.
- Point_of_Interest (POI) – instances of that concept may be physical or virtual locations or objects, which are considered to be of interest to a user and might serve as navigation destinations (*e.g.*, room, printer, coffee machine). In practice, a POI is represented through an *Exit*.
- Obstacle – obstacle denotes something that prevents the movement 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 movement of the user (*e.g.*, security policies, a hall that makes difficult the relocation of blind people). The latter type of obstacles is very important as it enables the definition of dynamic and non-physical obstacles.
- Corridor_Segment – the concept of a corridor segment is a construct devised to facilitate segmentation of the paths into atomic elements. A corridor segment belongs to only one corridor and connects exactly two *Path_Points*.
- Anchor – any passage, exit, navigational point or POI included in a path that can assist and be used in the presentation of the navigation plan. *Anchors* (or landmarks) cannot be moving objects. Examples of anchors are junctions, doors, escalators and elevators. Hence, anchors are mainly structural elements of buildings. However, non-structural elements, such as POIs, could also be used as anchors, *e.g.*, a coffee machine.

- Path – a sequence of interleaved *Path_Points*, which is capable of getting a user from its current position to a destination location. A path is characterised as *walkable* if it can be used by any 'normal' user (*i.e.*, not having disabilities or other navigation-related constraints). Apparently, the set of walkable paths in an indoor environment is the superset of all other path-sets, which are accessible by specific user classes. A path usually contains several POIs, anchors and obstacles. A subset of them, which is selected by the path selection rules, will be used for the final user navigation.

Table 1 summarises the most interesting ontology roles that interrelate the INO concepts and their semantics according to the OWL-DL terminology.

Table 1 Main roles of INO

Role name	*Domain*	*Range*	*Semantics*	*Description*
hasDescription	Passage	Description		The type of description of the passage (*e.g.*, image, audio or text)
represents	Exit	Passage	Functional (inverse)	An *exit* represents only one passage. A passage is represented by one or more exits (*e.g.*, the door passage is represented by one exit while an elevator is represented at least by two exits)
inFloor	Horizontal_ Passage	Floor	Functional	Each horizontal passage belongs only to one floor. The vertical passages are assigned a pair of attributes (*upperFloor, lowerFloor*)
leads	Path_Point	Path_Point	Symmetric and transitive	Any point leads transitively to other points in the topology graph
leads_directly	Path_Point	Path_Point	Symmetric	Any point is connected to its adjacent point. This role is a subrole of *leads*
isExcludedFor	Exit	uno:User		An exit that cannot be traversed by a user is 'marked' with this role. The *User* concept is imported from the UNO ontology

The aforementioned set of concepts cannot provide all the desired model expressiveness by itself. For that purpose, in the current version of INO, we have defined a concept named *Space* along with its subconcepts *Room*, *Floor*, *Corridor* and *Building* in order to assign position to POIs and users. Ideally, these should be imported from a spatial ontology. Currently, we are in the process of designing such an ontology, which will enable the description of generic indoor spatial environments and reasoning functionality on their instances.

4.1 User modelling with the user navigation ontology

4.1.1 Elements of navigational user modelling

According to Kikiras *et al.* (2006), a navigation-oriented User Profile (UP) is based on attributes from the following categories/components (see Figure 7):

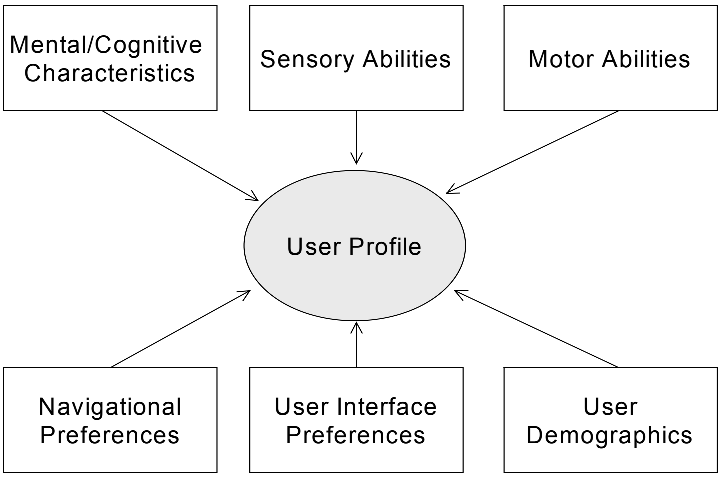
1. User demographics – basic user information such as name, age, gender, as well as a series of optional information, *e.g.*, communication details.
2. Mental/cognitive characteristics – all information pertaining to the user's mental/cognitive abilities, such as:
    - Consciousness functions – indicate the existence of possible malfunctions in the user consciousness abilities. Such abilities correspond to general mental functions that control the user's state of awareness and alertness.
    - Orientation disability – captures the user's orientation ability, which corresponds to knowing and ascertaining his/her relation to oneself, to others, and to the surrounding environment. Potential malfunctions in this ability significantly hinder the navigation procedure.
    - Mental disabilities – indicate whether the user has disabilities with respect to his/her mental functions (mental impairment, Alzheimer's disease, *etc.*).
    - Concentration to an objective – The World Health Organization defines this mental function as *the mental ability of an individual to remain focused on an external stimuli or an internal experience for a certain period of time*. Difficulty on this function is more often experienced in elderly people, teenagers and children.
    - High-level cognitive functions – this category considers difficulties in high-level cognitive functions, such as decision making, planning and execution of actions and plans, degradation of memory functions, *etc.* Potential malfunction of any of these functions may lead to difficulties for the user to understand and execute complex instructions in a timely manner. Therefore, a navigation system should be able to respond to such information by selecting proper paths and customising the routing instructions in a way suitable for a given user suffering from such impairments.
3. User's sensory abilities – sensory impairments affect the way a user exploits his/her sensing abilities (especially viewing and hearing) during wayfinding. This category is further divided to two subcategories: visual and hearing abilities.
4. User's motor abilities – captures a user's ability to move from one place to another with respect to the way he/she controls and coordinates his/her movement. Motor abilities refer to all kinetic abilities of users and not only to those associated with their mobility (although the latter are more important from the perspective of navigation). Users are categorised as having:
    - autonomous mobility without assistive devices
    - mobility supported by an escort (with or without assistive devices)

- autonomous mobility with wheelchair
- autonomous mobility with assistive devices (other than wheelchair).

5 Navigational preferences – This category captures the user's navigational preferences. Typical preferences are: selection of the shortest route first, selection of the fastest route, preference in most 'popular' path elements (*e.g.*, central corridors and stairs), avoidance of stairs, avoidance of crowded areas (*e.g.*, for blind users), *etc.*

6 Interface preferences – This category captures the user's preferences with respect to the means and the media in which he/she will receive routing instructions (*e.g.*, textual, audio, visual). It also depends on the user's mobile device.

Figure 7 Components of a navigation-oriented User Profile



4.1.2 User navigation ontology

All the components described in the previous section have to be specified in a suitable form to be applied in actual applications. Hence, we decided to represent them through a Semantic Web ontology. For that purpose, we adopted the OWL for describing the user classes and their properties.

For the development of the UNO ontology, we followed the directives of ontological engineering that promote ontology reuse and alignment between existing ontologies. Specifically, during ontology development, we have tried to extend some of the concepts specified in the GUMO ontology (see Section 2). An extract of the UNO concept hierarchy is shown in Figure 8, while Figure 9 illustrates the basic UNO properties. Informal definitions of the top-level UNO concepts follow (the definitions of properties are quite straightforward):

- Ability – the super-class of the various user abilities with regard to the navigation procedure. A user may have many abilities. Disabilities may be defined through the use of the Quality class values (see below).

- Demographics – value classes for user demographics (age, gender). Its subclasses are implemented as value partitions as dictated by the W3C Semantic Web Best Practices Group (SWBP, 2001).
- Quality – another class representing a value set for describing the degree/quality of the various abilities. Its values are ‘bad’, ‘medium’, ‘good’ and ‘perfect’. Obviously, a bad quality value for ability denotes a disability.
- User – an abstract class that subsumes the more specifically defined user classes.

The main difference between UNO and GUMO, apart from their scope, is that UNO is used actively in inference procedures, while GUMO provides a core knowledge base (*i.e.*, taxonomy and assertions of individuals) for basic classification of users and their characteristics. Hence, a key feature of UNO lies in the formal definition (through restrictions, and necessary and sufficient conditions) of user classes. In the current version of UNO, we have included a minimal set of possible classes. Each specific navigation application should extend this set appropriately. The use of the OWL-DL language enables very expressive user definitions. Indicative definitions (in mixed OWL and first-order-logic-like notation, for readers unfamiliar with Description Logics) of such *defined concepts* are:

YoungWheelchairedUser $\leftrightarrow$

$\exists$ hasAbility AutonomousWheelchairedMobility $\wedge$

$\exists$ hasAge LessThan18

VisuallyImpairedMaleAdultUser $\leftrightarrow$

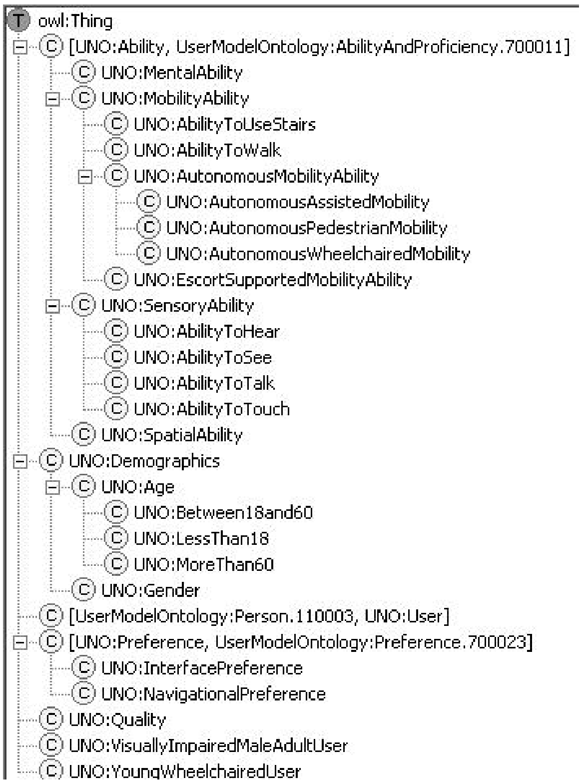
$\exists$ hasAbility (AbilityToSee $\wedge$ hasValue(hasQuality, bad)) $\wedge$

$\exists$ hasAge Between18and60 $\wedge$ hasValue(hasGender, male)

(Note: *hasValue* is an OWL reserved word)

After reasoning on an ontology with such defined user classes, these are classified under the generic user class and the various user instances are classified accordingly.

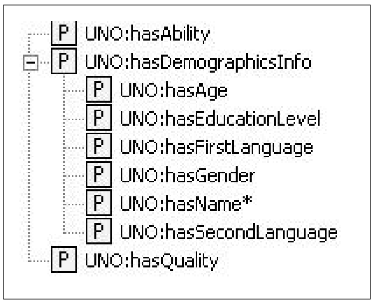
Figure 8 The basic UNO taxonomy



- owl:Thing
  - [UNO:Ability, UserModelOntology:AbilityAndProficiency.700011]
    - UNO:MentalAbility
    - UNO:MobilityAbility
      - UNO:AbilityToUseStairs
      - UNO:AbilityToWalk
      - UNO:AutonomousMobilityAbility
        - UNO:AutonomousAssistedMobility
        - UNO:AutonomousPedestrianMobility
        - UNO:AutonomousWheelchairedMobility
      - UNO:EscortSupportedMobilityAbility
    - UNO:SensoryAbility
      - UNO:AbilityToHear
      - UNO:AbilityToSee
      - UNO:AbilityToTalk
      - UNO:AbilityToTouch
    - UNO:SpatialAbility
  - UNO:Demographics
    - UNO:Age
      - UNO:Between18and60
      - UNO:LessThan18
      - UNO:MoreThan60
    - UNO:Gender
  - [UserModelOntology:Person.110003, UNO:User]
  - [UNO:Preference, UserModelOntology:Preference.700023]
    - UNO:InterfacePreference
    - UNO:NavigationalPreference
  - UNO:Quality
  - UNO:VisuallyImpairedMaleAdultUser
  - UNO:YoungWheelchairedUser

Note: The prefix *UNO* denotes a UNO class, while *UserModelOntology* denotes a GUMO class

Figure 9 The basic UNO hierarchy of properties



- UNO:hasAbility
- UNO:hasDemographicsInfo
  - UNO:hasAge
  - UNO:hasEducationLevel
  - UNO:hasFirstLanguage
  - UNO:hasGender
  - UNO:hasName*
  - UNO:hasSecondLanguage
- UNO:hasQuality

Regarding alignment with GUMO, some UNO classes are declared to be equivalent to GUMO classes (*e.g.*, Preference). Moreover, some individuals of GUMO have been transformed to primitive classes in UNO (*e.g.*, individual AbilityToTalk of GUMO class AbilityAndProficiency has been asserted as class AbilityToTalk in UNO).

Regarding demographics information, we have modelled some relevant GUMO instances as binary properties, since otherwise we would have to create a different instance of such information for each separate user. The aforementioned transformations (instances to classes and instances to binary relations) have been performed in order to enable more complex concept expressions for describing user classes. Finally, we should note that there are GUMO classes that have not been incorporated/aligned with the current version of UNO, although they are relevant to the domain of navigation. For example, the class Motion could be used for supporting dynamic tracking and route corrections and the class PhysicalEnvironment could support the context-aware adaptation of navigation instructions (*e.g.*, high noise level could trigger increase in the volume level of audio instructions).

4.2 Rules and reasoning

The path-selection rules are further categorised to *physical navigation rules*, *perceptual navigation rules* and *navigation preferences*. The path-selection rule-base applies such kind of rules with certain priorities. Actually, the physical navigation rules are applied first (*i.e.*, with high priority), in order to discard any paths that are not physically accessible by the user. The *perceptual navigation rules,* related to the user's cognitive status (*e.g.*, age, education) and sensory abilities, are applied next. Finally, paths that comply with the user preferences (*e.g.*, paths containing elevators) are identified after the application of the navigation preferences. The rules are described through the Semantic Web Rule Language-SWRL (Horrocks *et al.*, 2004). Such rules are of the form 'if *antecedents,* then *consequent*'. Hence, a rule is evaluated (*i.e.*, holds) if the antecedent-part of the rule holds. Some indicative rules are the following (the UNO user classes used in these rules are hypothetical and their definitions are analogous to those presented in Section 4.2):

Rule 1 (Physical navigation rule)

UNO:HandicappedUser(u) ∧ INO:Stairway(s) → INO:isExcludedFor(s,u)

Rule 2 (Perceptual navigation rule)

UNO:BlindUser(u) ∧ INO:hasDescription(pass,descr) ∧ INO:Textual_Description(descr) → INO:hasPerceptualPenaltyFor(pass,u)

Rule 3 (Navigation preference)

UNO:LazyUser ∧ INO:Motor_Passage(p) → INO:hasPreferentialBonusFor(p, u)

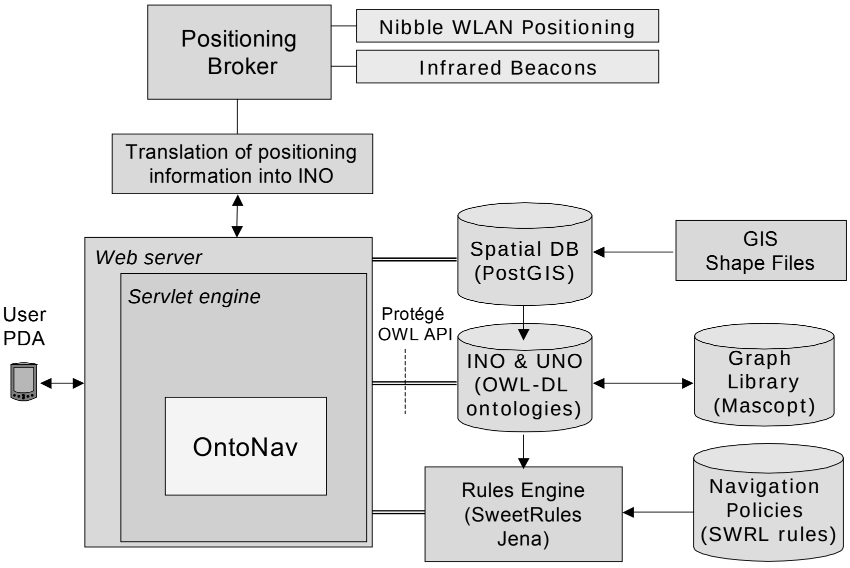
Some of these rules 'mark' the path elements that should be excluded from the user-compatible topology graph (through the isExcludedFor property), while others reward/penalise some path elements (through the properties hasPreferentialBonusFor, hasPreferentialPenaltyFor, hasPerceptualBonusFor hasPerceptualPenaltyFor, *etc.*). The final ranking of the user-accessible paths is based on such reward/penalty assertions and on the path length, which always remains a key selection criterion.

5 Implementation and performance evaluation

5.1 Implementation details

The OntoNav system has been implemented with open technologies, which ensure platform independence. Figure 10 shows the physical architecture of OntoNav along with the implementation technologies. The application logic of the system has been implemented as Java servlets, deployed in an Apache Tomcat server. The building blueprints, along with the necessary metadata, are exported from ESRI (1998) shapefiles and stored in a PostGIS (2005) spatial database. The shapefiles are created with a common GIS system and the metadata contain additional annotations for the characterisation of the GIS thematic layers (in fact, each thematic layer corresponds to one *Path_Point* concept). A detailed description of the shapefile creation process is described in the following section. By using custom data extraction code, the INO ontology is populated with the database data and the *path graph* is created, with the aid of the Mascopt (2005) graph library. This library also provides an implementation of the *k Shortest Paths* algorithm. As already mentioned, INO as well as UNO are written in the DL sublanguage of the OWL DL and are programmed through the Protégé-OWL API (Knublauch *et al.*, 2004). In UNO, a new user instance (*i.e.*, user profile) is created each time a new user registers to the service. The classification of the user according to its profile is performed with a DL reasoner, provided by the Jena Framework (Carroll *et al.*, 2004). The rule-based inference of the user-compatible INO portion has been provided by the SweetRules (2005) suite of tools, which support SWRL, the emerging rules standard for the Semantic Web. The positioning system consists of two symbolic location detection technologies: (a) the Wireless LAN positioning engine Nibble (Castro *et al.*, 2001), developed at the UCLA University, and (b) infrared beacons, manufactured by LessWire (2005). However, we have already adopted and implemented a more advanced positioning mechanism, based on multi-sensor location fusion, as discussed in Sekkas *et al.* (2006).

Figure 10 Implementation technologies of OntoNav



5.2 Evaluation set-up

For a preliminary evaluation of the navigation system, we have set up a scenario with a single user. The set-up details are as follows:

- The navigation space is an imaginary three-floor building. The blueprints of the first and third floor are shown in Figures 11 and 12, respectively. In these figures, the graphs that represent the set of paths are also depicted. These graphs contain at most (*i.e.*, for a user without any mobility disabilities) 143 nodes (Path_Points) and 410 directional arcs (twice as many as the passages).
- The user profile is specified in Table 2.
- The path selection rules are described in Table 3.
- The system computes the three shortest paths (*i.e.*, k = 3), if such number is attainable, and the respective degree of appropriateness for each one.

Figure 11 First floor blueprints

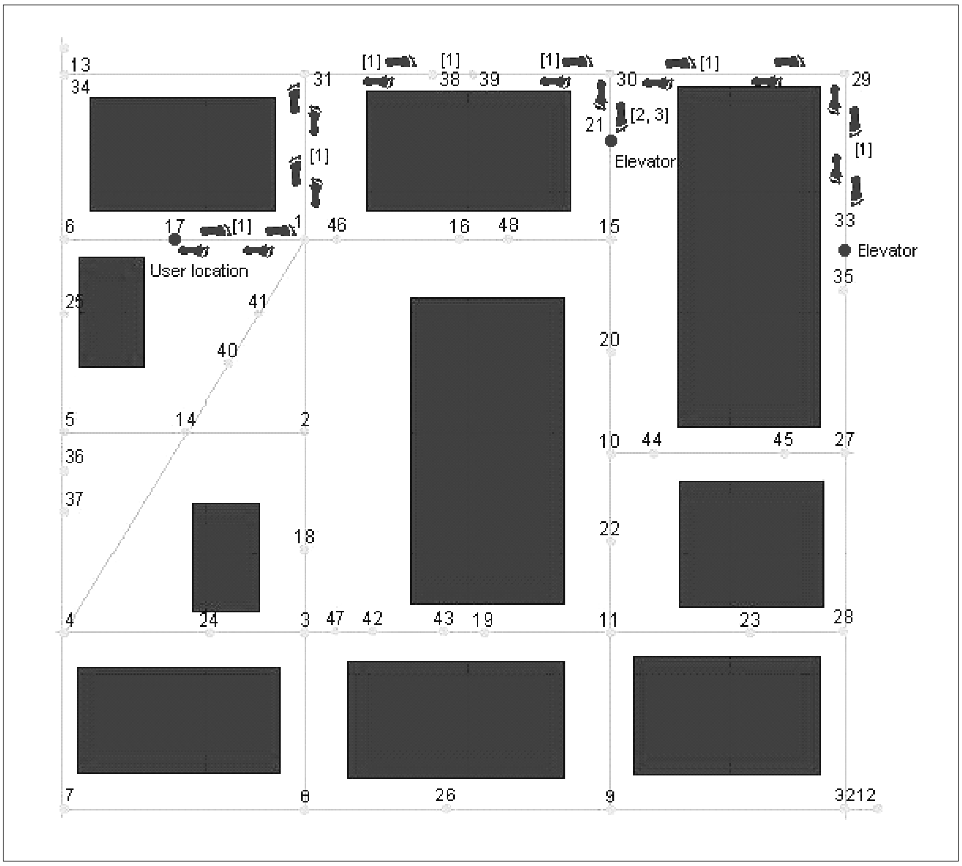


Figure 12 Third floor blueprints

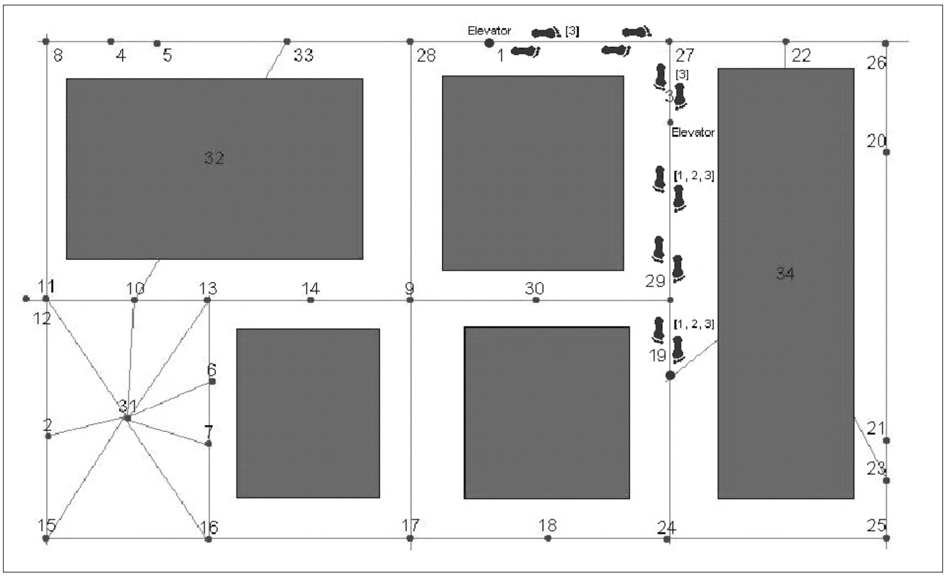


Table 2 The user profile for the evaluation scenario

canWalk	*isBlind*	*isPregnant*	*hasCardiopathy*	*IsLazy*	*Age*
√	√		√		Middle-aged

Table 3 Path selection rules

Uno:HandicappedUser(u) & ino:Stairway(s) → ino:isObstacleFor(s,u)

Uno:HandicappedUser(u) & ino:Escalator (e) → ino:isObstacleFor(e,u)

Uno:HandicappedUser(u) & ino:Corridor_Stairway(cs) → isObstacleFor(cs,u)

Uno:LazyUser(u) & ino:Motor_Passage(mp) → ino:hasPreferentialBonusFor(mp,u)

uno:CardiopatheticUser(u) & ino:Stairway(s) → ino:hasPreferentialPenaltyFor(s,u)

uno:CardiopatheticUser(u) & ino:Elevator(e) → ino:hasPreferentialBonusFor(e,u)

uno:BlindUser(u) & ino:Junction(j) → hasPerceptualPenaltyFor(j,u)

The first metric used for evaluating the system performance is the Response Time (RT), *i.e.*, the time duration between the submission of a navigation request and the formulation of the response (best path). RT depends on the Execution Times (ET) of the various system components. In order to have a detailed view on such dependencies, we measure each separate execution time:

ET_R – the execution time of the reasoner that classifies the user.

ET_S – the execution time of the rule engine SweetRules.

ET_G – the execution time for the graph creation from the ontology instances.

ET_K – the execution time of the kSP algorithm.

Hence, it holds that:

$$RT = ET_R + ET_S + ET_G + ET_K + ET_{Other}$$

where ET_{other} is the time spent in other system procedures (I/O routines, screen output, web server delays, *etc.*).

The computer system used for the experiments was a typical PC with the following characteristics:

- CPU: Intel Pentium 4 (3 GHz)
- RAM memory: 1 GigaByte
- Operating System: Windows 2000 Server
- no special tuning.

5.3 Evaluation results

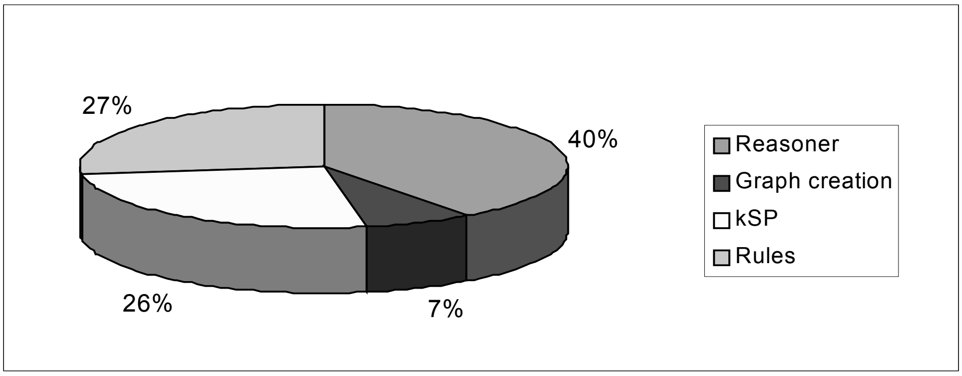
Table 4 and Figure 13 show the average response time and how it is shared among the various systems processes. Average values were calculated from 10 identical user requests. From these measurements, we observe that the largest portion of time is due to the user classification (DL reasoning). The rule executions and the routing algorithm require comparable portions of the response time. On the other hand, the graph creation from the INO instances is a much more lightweight task. Finally, ET_{Other} can be omitted. In every different test execution, RT was greater than 3.1 seconds and lower than 4 seconds. We have assumed that the system has been initialised (see Figure 3). Without this assumption (*i.e.*, in the first user request), RT may be more than ten seconds.

The above measurements are quite promising. Furthermore, if we assume that (1) the user is known to the system (*i.e.*, the user has already specified his/her profile and has used the service) and (2) that the building elements are not modified (a rather reasonable assumption), then no user classification, rule execution and graph creation are required for each individual request. This implies that only the execution time, ET_K, of the routing algorithm is executed and, thus, the RT approximately one second.

Table 4 Average response time and average execution times (in milliseconds)

ET_R	ET_G	ET_K	ET_S	ET_{other}	RT
1398.3	253.1	903.1	948.6	10.8	3513.9

Figure 13 Distribution of total response time



5.4 Service execution example

The results of the navigation service execution, with origin location *Room_Exit17_1* and destination location *Room_Exit19_3* are shown in Figure 14. The path elements' names are termed after the convention *PathElementID_FloorID*. Hence, *Room_Exit19_3* denotes the Room_Exit with ID = 19 in the third floor. The paths of Figure 14 are indicated with footprints in Figures 11 and 12. The computed paths are presented as ordered concatenations of (→) and path element names. In Figures 11 and 12, the numbers in the brackets next to path-segments (arcs) indicate which paths (Figure 14) they belong to.

Figure 14 Sample execution result

Path ID: 1 (length = 4.515)

Room_Exit17_1 → **Corridor_Segment4** → Junction1_1 → **Corridor_Segment1** → Junction31_1 → **Corridor_Segment50** → Stairway_Exit38_1 → **Corridor_Segment54** → Ramp_Exit39_1 → **Corridor_Segment49** → Junction30_1 → **Corridor_Segment47** → Turn_Point29_1 → **Corridor_Segment48** → Elevator_Exit33_1 → **Elevator3** → Elevator_Exit51_2 → **Elevator3** → Elevator_Exit3_3 → **Corridor_Segment144** → Junction29_3 → **Corridor_Segment171** → Room_Exit19_3

Preferential Bonus = 2, Preferential Penalty = 0, Perceptual Bonus = 0, Perceptual Penalty = 4

Path ID: 2 (length=4.519)

Room_Exit17_1 → **Corridor_Segment4** → Junction1_1 → **Corridor_Segment1** → Junction31_1 → **Corridor_Segment50** → Stairway_Exit38_1 → **Corridor_Segment54** → Ramp_Exit39_1 → **Corridor_Segment49** → Junction30_1 → **Corridor_Segment41** → Elevator_Exit21_1 → **Elevator1** → Elevator_Exit35_2 → **Corridor_Segment106** → Junction22_2 → **Corridor_Segment108** → Elevator_Exit51_2 → **Elevator3** → Elevator_Exit3_3 → **Corridor_Segment144** → Junction29_3 → **Corridor_Segment171** → Room_Exit19_3

Preferential Bonus = 2, Preferential Penalty = 0, Perceptual Bonus = 0, Perceptual Penalty = 5

Path ID: 3 (length = 4.526)

Room_Exit17_1 → **Corridor_Segment4** → Junction1_1 → **Corridor_Segment1** → Junction31_1 → **Corridor_Segment50** → Stairway_Exit38_1 → **Corridor_Segment54** → Ramp_Exit39_1 → **Corridor_Segment49** → Junction30_1 → **Corridor_Segment41** → Elevator_Exit21_1 → **Elevator1** → Elevator_Exit35_2 → **Elevator1** → Elevator_Exit1_3 → **Corridor_Segment138** → Junction27_3 → **Corridor_Segment143** → Elevator_Exit3_3 → **Corridor_Segment144** → Junction29_3 → **Corridor_Segment171** → Room_Exit19_3

Preferential Bonus = 2, Preferential Penalty = 0, Perceptual Bonus = 0, Perceptual Penalty = 5

Note: Bold font: passages, normal font: Path_Points
The path lengths are not expressed in real distance units.

6 Conclusion and future work

The introduction of knowledge engineering technologies in traditional services and applications is expected to rapidly spread in the following years. This 'paradigm shift' in system design and implementation is merely 'pushed' by initiatives such as Inclusive Design and Universal Access (Stephanidis and Savidis, 2001). There are still a lot of open issues, however, before such approach can be massively adopted in commercial systems. One of the greatest challenges is the common definition and adoption of semantic application domain models (*i.e.*, ontologies). In our case, INO and UNO ontologies should have been standardised in some way, so that LBS providers could rely on their specifications in order to develop interoperable semantic navigation services. Moreover, ontological engineering is a very demanding process. Towards simplifying it, there is a great deal of past and current research in developing methodologies and tools for creating, managing, merging and updating ontologies (Gomez-Perez *et al.*, 2004). In addition, more and more research projects have commenced to design ontologies for specific application domains. Their attempts, if coordinated accordingly, can result in the creation of an extensible 'ontology repository' usable by anyone.

The proposed approach to designing navigation services, directly involves human factors. Hence, another issue is the human evaluation of such systems, apart from their performance evaluation. Since Semantic LBS are (according to the definition in Section 2.2) human-centred, user acceptance and quality assessment are considered as prerequisites before launching them in real-world systems. The parameters that affect the path selection process should be adjusted carefully by real users prior to system deployment. In the future, we expect to see more research in user evaluation of innovative personalised mobile services. Pervasive computing research has already paved the way for such evaluation frameworks (Scholtz and Consolvo, 2004), but much progress still has to be achieved.

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