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An indoor routing algorithm for the blind: development and comparison to a routing algorithm for the sighted

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This paper presents a prototypical implementation of a non-network-based indoor routing algorithm for the sighted and the blind. The spatial abilities of the visually impaired are discussed. Former approaches of outdoor navigation systems for the blind are analyzed and deemed inappropriate for the purpose of modeling indoor navigation. The proposed routing algorithm for the blind calculates routes based on physical characteristics of traveling with a long cane. The algorithm distinguishes between clues, landmarks, obstacles, and hazards along the feasible paths and selects the optimal route by trading off distance and the number of landmarks and clues along a route. Subsequently, the routes for the blind are compared to routes calculated by a the routing algorithm for the sighted. The paper asserts that the proposed indoor routing algorithm leads to more suitable routes for the blind.

Keywords: non-network-based routing algorithm; indoor navigation; wayfinding; visually impaired

1 Introduction

The World Health Organization (2004) reported that there are at least 161 million people worldwide with visual impairments, of whom 37 million are considered legally blind. As estimated by the American Foundation for the Blind (2007), approximately 1.3 million Americans were reported legally blind in 1994-95. In order to move around in their everyday environments, many disabled and elderly people in the U.S. are using a long cane. Among the blind population, the white cane, commonly referred to as the long cane, is the primarily used assistive technology device. Aging and legal blindness are strongly correlated. Almost two thirds of the blind population in the U.S. are older than 65 (Chiang et al. 1992). It is expected that the number of elderly persons will have doubled by the year 2030 (U.S. Bureau of the Census

1996, 2001). These demographic numbers imply that there will be a significant increase in the number of people with visual impairments and other aging-related disabilities during the next three decades.

It is commonly accepted that the incapability of moving freely and independently can hinder the full integration of an individual into society (Golledge et al. 1996). Blindness, like other disabilities, affects one's mobility and quality of life (Tuttle and Tuttle 2004), especially when the vision loss occurs at a later stage of adulthood after a lifetime with functional vision (Donohue et al. 1995, Horowitz and Reinhardt 1998, Horowitz 2003).

In the absence of visual input, the blind person must rely on the remaining senses to obtain continuous information about the environment in order to perform wayfinding tasks. When using a mobility device, such as the white cane, the wayfinding performance of the user depends on the individual wayfinding skills and preexisting knowledge of the environment. Electronic navigation systems can help to bolster the wayfinding performance of the blind person by providing supplemental information about the environment.

There has been an increasing number of outdoor navigation systems for the blind. Indoor navigation, on the other hand, has not been given special attention so far. Most of the outdoor systems follow approaches similar to those of car navigation systems, both in conceptualization and functionality. Operating on a network-based abstraction of space and employing Global Positioning System (GPS) and Geographic Information System (GIS) technologies, they acquaint the user with contextual information along the path of travel. The provided information includes the location of landmarks, turning instructions, and details about the general layout of the surrounding area that extend the user's perception of the environment beyond the possibilities given by direct exploration of the immediate space or object space (Freundschuh and Egenhofer 1997). One commonly neglected aspect of these systems, however, is obstacle avoidance.

In this paper we present non-network-based indoor routing algorithms for the sighted and the blind. In the case of the blind, the algorithm calculates routes based on the actual wayfinding behavior of blind cane travelers. Our efforts are not aiming at the replacement of the white cane as the primary mobility device but at the calculation of an indoor route that can be considered optimal for the blind when traveling with the white cane. As we will argue in the paper, for modeling indoor navigation it is unsuitable to employ a network-based representation of space as networks constrain movement to a static set of premeditated routes. Instead, we employ a two-dimensional representation of space in which a route is calculated based on principles of Orientation and Mobility (O&M; e.g. Hill and Ponder 1976). O&M entails the methods, techniques, aids and instructions, which are aimed at helping the visually impaired to obtain or reacquire the skill of traveling safely and independently

(Welsh and Blasch 1980).

Additionally, we argue that the characteristics and principles of indoor cane travel supersede distance minimization as primary criterion for the determination of an optimal route for the blind. In other words, opposed to the case of the sighted, distance minimization gains importance not by itself but in combination with other route selection criteria that result from the physical specificities of traveling with the cane. Based on our analysis of work in O&M, we hypothesize that *a routing algorithm that integrates the principles of indoor cane travel accommodates the information needs of the blind person for orientation and safety as opposed to an algorithm that relies on distance minimization as the only route selection criterion.* To elucidate the latter point we compare and evaluate the results of the routing algorithm for the blind and the sighted in terms of safety, length, and the number of encountered objects that aid in orientation.

In the next section we introduce related work in the area of human wayfinding and navigation. Furthermore, we discuss research on spatial abilities of the visually impaired and give an overview of outdoor navigation systems for the blind. Section 3 presents differences between these outdoor navigation systems and the proposed indoor routing algorithms. We also refer to important principles of O&M and their implications for our algorithm for the blind. Section 4 presents the scenarios and the conceptual model that underlies the routing algorithms. In section 5 we continue with a technical description of the routing algorithms from an implementation perspective. Routes for the blind and the sighted are compared and the results discussed. Section 6 provides conclusions and gives suggestions for future research directions.

2 Related work

2.1 *Navigation and wayfinding*

Navigation is a process that consists of the cognitive act of wayfinding and the physical act of locomotion, including, for example, obstacle avoidance (Darken et al. 1998, Montello 2005). Wayfinding behavior can be described as purposeful, directed, and motivated movement from an origin to a specific distant destination that cannot be directly perceived by the traveler (Golledge 1999, p. 6).

Landmarks, a key component in wayfinding and navigation, help a person to stay oriented and maintain a sense of being on-route (Allen 1999a). As such, they are important choice points for spatial behavior and usually associated with characteristic features in the environment (Burnett 2000, Raubal and Winter 2002, Tversky 2003). In addition, they facilitate the organization and categorization of information about the environment (Golledge et al. 1992).

May et al. (2003) demonstrated that landmark information was by far the most frequently demanded category of information for a pedestrian outdoor navigation system in an urban environment. The importance of landmarks for human wayfinding is apparent at all scales, not only for the sighted (Wang and Brockmole 2003, Mou et al. 2004) but also the visually impaired population (Passini and Proulx 1988, Espinosa et al. 1998). However, in general, the sets of particular landmarks chosen by the sighted and the visually impaired for the same route are very different (Passini and Proulx 1988) or even disjoint (Golledge 1991).

Allen (1999a) elaborated on the cognitive abilities involved in human wayfinding. He suggested a framework based on the distinction between *wayfinding tasks* (the purpose of the wayfinding activity) and *wayfinding means* (the specific wayfinding techniques employed by a person) to accomplish these. Two important wayfinding tasks that apply to the scenarios in this paper are *explore* and *quest*. Explore encompasses traveling in an unfamiliar environment in order to learn about its layout. Quest is similar to explore in the sense that it involves traveling to unfamiliar places. The difference, however, is that in a quest the knowledge of the location of a specific destination is conveyed before the beginning of the journey, e.g. through a map or verbal description.

Wayfinding means utilized in the formerly mentioned wayfinding tasks are *piloting* and *path integration* (Allen 1999b). Piloting refers to the ability of following a sequence of landmarks while maintaining and updating positional information in relation to a single or multiple landmarks. Path integration is comprised of velocity- and acceleration-based wayfinding and relies on information on one's heading and bearing relative to a point of origin (Loomis et al. 1999). During wayfinding, humans, either sighted or visually impaired, take advantage of both methods rather than relying on only one of them. Golledge and Stimson (1997) reported that dividing a route at critical choice points into an array of segments and remembering their sequence and the angles between them (i.e. piloting) is the most common wayfinding technique applied by the visually impaired.

2.2 *Spatial abilities of the visually impaired*

A vast amount of research has been conducted on the performance of the visually impaired on spatial tasks. Fletcher (1980) divided the underlying theories into three categories (see also Andrews 1983, Golledge and Stimson 1997, Ungar 2000, Kitchin and Blades 2002). The *deficiency theory* proposes that the absence of visual experience prohibits the understanding of spatial concepts (Golledge and Stimson 1997). According to this theory, vision is constituted to be the only sense through which spatial relationships, such as distance and height, can be learned and fully understood (Ungar 2000). This view is supported by the work of the German physician von Senden (1932, cited in Fletcher 1980, Ungar 2000). Von Senden collected accounts of early blind subjects who gained sight after surgery in the course of the discovery of safe operative treatments for cataract. He interpreted the problems of the former blind to process spatial information through vision as a consequence of their lack of cognitive representations of space and size (Ungar 2000). More recent research, however, has provided ample evidence for the spatial competence of the visually impaired, encouraging the abandonment of the deficiency theory.

Fletcher classified two other theories, in particular the *inefficiency theory* and the *difference theory*. The inefficiency theory states that blind persons possess the same range of spatial skills as sighted ones, but their performance is necessarily less efficient, since they have to rely on non-visual stimuli only. The difference theory, on the other hand, posits that the spatial abilities of the blind are qualitatively different in that they use different coding strategies, but, functionally, they are equivalent to those of the sighted. Empirical evidence in support of either theory can be found. However, Ungar (2000) asked how far studies bolstering the inefficiency theory assessed the blind population's full cognitive potential rather than individual spatial competencies. Another point of concern stems from the work of Blades et al. (2002). In an experiment on the performance of human subjects on route learning, they showed that performing a spatial task, such as pointing to specific landmarks, has an effect on the early stages of the route learning process itself. Thus, findings of earlier studies should be reexamined for a dependency between the design of the experiment and the observed outcomes.

In a study about the spatial abilities of blindfolded sighted, adventitiously blind, and congenitally blind subjects, Loomis et al. (1993, see also Klatzky et al. 1995) found no significant differences among the participating groups in their performance on simple and complex navigation tasks involving distance estimation and reproduction, triangle completion and pathway retrace. The authors suggested the possibility of bias in the selection process of the subjects as a possible explanation for the contrast to the results of the study of Rieser et al. (1986), which Loomis et al. (1993) tried to reproduce. In their experiment on one's sensitivity to changes in the spatial relationship between oneself and surrounding objects during locomotion, Rieser et al. (1986) reported a worse performance of the congenitally blind subject group.

In a series of eight tasks, Passini et al. (1990) assessed various spatial abilities of the congenitally totally blind, adventitiously totally blind, and the visually impaired with some residual vision. The tasks assessed, among others, the performance and accuracy on route learning, pathway retrace, mental rotation, and the reproduction of learned layouts. Even though the members of the visually impaired groups tended to need more time than their peers in the sighted control group to accomplish the tasks, their results clearly suggest that spatio-cognitive competence can be acquired without any prior visual experience.

2.3 *Navigation systems for the blind*

In 1995, Strothotte et al. presented their findings on the MoBIC project (Mobility for Blind and elderly people Interacting with Computers). The MoBIC travel aid is constructed for outdoor navigation and consists of two components: (1) a route planning systems (MoPS), which allows the user to inspect electronic maps of the route using a touch tablet with auditory feedback and (2) a navigation system (MoODS), which assists the blind person with orientation information while she is in the field. Information deemed relevant are details about the current route segment (e.g. surface type), distance to the next route segment, intersections, landmarks, and timetables of buses and trains. Strothotte et al. note that "the MoBIC system itself is intended for the informational needs of travellers with respect to their overall journey. It does not provide information on a low level, such as whether there is an obstacle temporarily blocking the way. Such information must be obtained in other ways, such as using the long cane" (p. 5). MoBIC employs a route calculation algorithm that minimizes travel time or total walking distance while observing preferences of the blind for ease of travel (Douglas et al. 1997).

The research activities of Loomis et al. in the area of navigation without sight span over a period of twenty years. One of their goals is the development of a personal guidance system for the blind (Golledge et al. 1998). In order to produce a user-oriented marketable product, Golledge et al. (2004) conducted a telephone survey about the preferences for the components of a possible guidance system. So far, the system consists of three modules: (1) A module for determining the position and orientation of the traveler using GPS, (2) a GIS module, and (3) the user interface (Loomis et al. 1998). The system computes a path to a selected destination by minimizing the total distance (Golledge et al. 1998). It informs the user about features on or near the route. Other information includes instructions on when to turn and the distance to the destination.

Helal et al. (2001) developed a wireless pedestrian navigation system for the blind called Drishti. Operating on a network representation of walkways of the University of Florida campus, Drishti selects routes based on user preferences and provides the user with information about landmarks and environmental conditions. It employs GIS technology to store and maintain environmental data and GPS to track the location of the user. The user can also extend the database with personal navigational information. The system is capable of dynamically rerouting the user if the initially calculated route is blocked.

As in the earlier cases, the system constrains movement to premeditated route segments by employing a network representation of space.

In 2002, Ross and Blasch presented their results on the development of a wearable orientation device. They proposed a prototype, which provides directional information based on the user's starting point and the direction of movement. The heading was measured by a digital compass attached to the user's head or body. The main focus of Ross and Blasch was on the design of the user interface. They employed three different approaches for enabling interaction between the user and the prototype (virtual beacon, speech output, and tapping output) and tested these in an outdoor setting. The prototype was programmed to provide directional information to a user walking from one side of the street to the opposite in an efficient and safe manner. Efficient and safe in this context is based on techniques from O&M and means crossing the street by minimizing direct exposure to traffic. Fifteen subjects tested the three interfaces and the quality of the prototype for accomplishing the street crossing task without drifting into the center of the intersection. Subjects using the tapping interface showed the best overall performance and the majority indicated that they prefer the tapping interface over the other interfaces.

3 Indoor wayfinding principles of the blind

3.1 *Differences to outdoor navigation systems for the blind*

One goal of this paper is the development of an indoor routing algorithm for the blind. Navigation encompasses the planning and execution of a route between an origin and a destination while concurrently maintaining orientation (Loomis et al. 1999). The purpose of the indoor routing algorithm is therefore the calculation of the optimal route that encompasses principles of wayfinding as commonly applied by the blind in a built environment. Before referring to what constitutes the optimal indoor route, we will first discuss the differences of our approach with respect to earlier work on outdoor navigation systems.

The prevalence of outdoor navigation systems built on network representations situated in environmental space (i.e. a large space that requires locomotion to experience it; see Freundschuh and Egenhofer 1997, p. 11) is obvious. Network nodes are usually associated with salient environmental features such as street intersections. The calculation of a route proceeds similar to car navigation systems. Route segments are selected from the set of all segments and combined so that the total distance is minimized. In some instances, edges are associated with additional attributes which may be tested against user preferences, leading to the exclusion of those edges that do not match the imposed constraints. In either case, the modeled movement of the user is limited to the segments stored in the database before the route calculation occurs.

It is counter-intuitive that the same conceptualizations apply to both pedestrian navigation systems and navigation systems found in cars: Pedestrians are not constrained to edges of a network, therefore a network-based representation is too abstract and cannot easily capture the various possibilities for the wayfinder's movements. A similar point has been made by Rüetschi and Timpf (2005), who refer to the structural distinction between network and scene space with regard to modeling wayfinding in public transport. In order to allow for movement between all objects in a room, one would have to introduce connections between all possible pairs of objects. Accessibility, however, would be restricted to objects, excluding points of destination other than features within the room. Additionally, obstacle avoidance would have to be accounted for by introducing more nodes and connections to the network. Using the latter approach, obstacle avoidance would be implied by the structure of the network but not explicitly accounted for by the system.

The resulting routes would be far from realistic when compared to routes actually taken by human beings. On paths traveled by pedestrians, either sighted or visually impaired, obstacle avoidance is a key factor for the selection of the best route and should be modeled explicitly for indoor navigation. The design of a potential navigation service should provide for the detection of obstructions and the calculation of detours. We conclude that the abundance of possibilities for creating a network, the lack of explicit obstacle avoidance, and the problem of route optimization render a network representation impractical for an indoor routing algorithm.

In order to answer the initial question of what constitutes the optimal indoor route, we distinguish between the sighted and the blind. In the case of the sighted, the answer is rather simple. As posited by Gärling (1999), we assume that when distance is the only criterion to assess the utility of a spatial choice, then it should be minimized. This can be achieved through a route that minimizes the Euclidean distance between two points as long as no obstacles obstruct the direct path. Otherwise the shortest detour around the obstacles encountered in the direct path must be found.

Next we will discuss relevant principles of Orientation and Mobility underlying wayfinding by the visually impaired. These are crucial to elucidate which route may be considered optimal for the blind. Consequently, they serve as the foundation for the development of the routing algorithm for the blind.

3.2 *Orientation and Mobility principles*

The purpose of O&M is to teach persons with visual impairments how "to travel safely, efficiently and gracefully through any environment under all environmental conditions and situations" (Jacobson 1993, p. 3). In individualized sessions, an O&M instructor teaches a student appropriate techniques for various situations (e.g. obstacle avoidance and self-protection), with the goal of equipping the student with travel skills that can be applied in different environments (Mettler 1995).

3.2.1 ***Trailing, alignment, and self-familiarization techniques.*** A reoccurring lesson early on in O&M curricula is the teaching of techniques that help the visually impaired to maintain a straight path of travel. One of these techniques is *walltrailing*, with the hand or the cane. The purpose for teaching these techniques beyond facilitating straight-line travel is (1) to provide the traveler with the means to determine the location of objects "along a wall or building line" (LaGrow and Weessies 1994, p. 110) and (2) to "enable the student to remain cognizant of his position in space by keeping in constant contact with the environment" (Hill and Ponder 1976, p. 29).

In a western culture, with rooms built with 90 degree angles, the visually impaired utilize walls to align themselves in order to establish a straight line of travel, either parallel or perpendicular to a specific wall (Hill and Ponder 1976). Walls are also central to systematic search patterns that enable the student to acquaint herself with an unknown environment. Two techniques are commonly employed indoors by the visually impaired. The more basic of these patterns, the perimeter familiarization (Jacobson 1993), uses a home base, usually a door, to explore the layout of the room. The visually impaired person traces each wall individually and returns to the home base before proceeding to the next wall. This process continues until she has thoroughly explored all walls and noted the distinguishing attributes of encountered objects, including their location in relation to one another. The goal of perimeter familiarization is to develop a cognitive representation of the room (Jacobson 1993). The second approach, the grid pattern, builds upon perimeter familiarization and also acquaints the traveler with the interior of the room (LaGrow and Weessies 1994).

3.2.2 ***The touch technique.*** An integral part of the O&M curriculum is the education in principles of traveling with the white cane. One standard cane technique is the *touch technique* (Hill and Ponder 1976, LaGrow and Weessies 1994). As LaGrow and Weessies suggested, independent travelers use this technique in over 90 percent of all cases. It enables the blind pedestrian to detect drop-offs and obstacles in the path of travel up to the height of the waist. The visually impaired person grasps the cane with the index finger extended against the side of the grip so that it points towards the tip of the cane. The hand, with its back facing to the side (as in a handshake), is positioned on the body's center line in front of the waist. The tip of the cane should rest on the ground approximately one meter in front of the body. By flexing the wrist, the cane is moved from side to side covering at least the whole width of the shoulders. When walking, the placement of the forward foot on the ground should occur simultaneously with the contact of the tip on the side opposite to that foot. Ideally, the spots where the tip touched the ground are the same as those spots where the feet are placed, ensuring that the area that the feet occupy is clear before the steps are actually taken.

3.2.3 ***Obstacles, hazards, clues, and landmarks.*** In general terms, the visually impaired need information about (1) objects in their immediate vicinity and (2) objects in the surrounding environment (Working Group on Mobility Aids for the Visually Impaired and Blind 1986). The first point refers to objects that have an impact on the safety of the blind traveler and her ability to orient herself in the environment. The second refers to information about orientation points in the environment not directly situated on the traveled route. For the purpose of this paper, we will discuss the first information need in detail because it directly influences the way in which the algorithm calculates a suitable route for the blind. Objects in the surrounding environment are only considered if they can be perceived by a blind person when traveling on a specific route.

Research in O&M suggests a classification of objects into obstacles, hazards, clues, and landmarks. Clues and landmarks are related concepts. Hill and Ponder (1976) defined clues as perceivable stimuli (auditory, olfactory, tactile, kinesthetic, or visual) which the blind person can use, amongst others, to determine her location in space. Similar to the definitions given in section 2, Jacobson (1993) defined a landmark as a constant and permanent configuration of a single clue or group of clues that are uniquely identifiable in an area. Considering a single object, a sparkling water fountain in the lobby of a hotel could be a suitable landmark for that area (because it is emitting a particular sound and has a distinct shape), but a ceiling fan between two cubicles in an office building rather not (only in the uncommon case, where the fan is unique in its environment). According to Wardell (1980), an obstacle is "an architectural or environmental obstruction in the path of travel that can be detected and negotiated" (p. 479) using standard cane techniques. He suggested that a hazard, on the other hand, is an obstruction that cannot be detected by the cane because it is located above the area covered by the cane. Among those items considered hazards, pendent objects at the height of the face or chest may be an eminent threat to the health of the visually impaired person (Wardell 1980).

The grouping of objects into obstacle or hazard, and clue or landmark is not mutually independent. It is clearly possible for some clue to fulfill the definition of an obstacle, as might be the case for environmental features, such as pillars, plants, or statues. The benefit of the distinction between obstacle or hazard, and clue or landmark, though, is that it enables us to relate the concept of safe travel and orientation to attributes of specific objects.

3.3 *Implications for the proposed indoor routing algorithm for the blind*

The previous considerations form the basis for the proposed indoor routing algorithm. The trailing, alignment, and self-familiarization techniques indicate that walls play a central role for a blind person when traveling with a cane in unfamiliar environments. In addition, walls aid in the process of orientation by providing continuous contact with the environment so that the blind person can determine her relative position in space (LaGrow and Weessies 1994). The latter aspect points to a quality of walls similar to clues and landmarks. Walltrailing should therefore serve as core principle for the calculation of the route for the blind. If possible, the algorithm should place the route parallel to the closest wall so that the blind person can trail it with the cane. With one of the doors as starting point, the blind person can trail the walls either clockwise or counter-clockwise to get to the destination, yielding two possible routes. If the destination is located off the wall towards the center of the room, then the segment that bridges the gap between the point where the blind person leaves the wall and the destination should be minimized. The segment should also be perpendicular to the wall so that the blind person can use it for proper body alignment.

In order to assure the safety of the blind person during navigation, the algorithm should account for obstacles and hazards that obstruct the route along the wall and find a suitable way around them. Another important aspect that impacts safety is the cane technique. The indoor routing algorithm should establish routes ensuring that the full cane sweep can be maintained. Thus, the resulting routes should be constrained to pathways which are at least as wide as the shoulder width of the blind person.

Landmarks and clues are important elements for orientation. Orientation itself is an integral part of navigation. The indoor routing algorithm should therefore consider these concepts for the selection process of the optimal route for the blind. Unlike the general case for the sighted, distance is not the only criterion that determines the optimal route. Rather, the total number of landmarks and clues are additional criteria that should influence the route selection. As suggested by Gärling (1999), we apply a trade-off between the criteria which are comprised of distance and the total number of landmarks and clues.

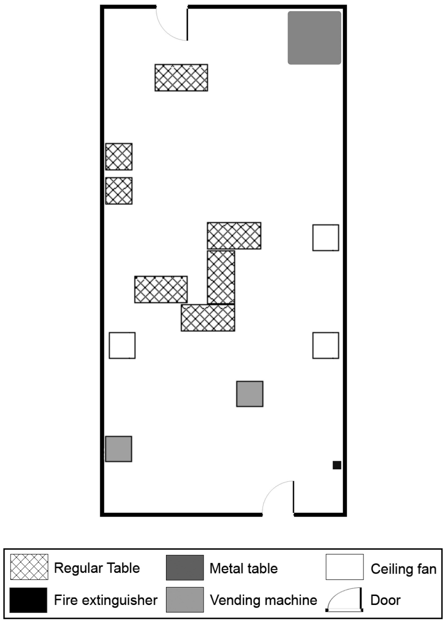

Figure 1. Schematic overview of the cafeteria. North ↑

4 Description of scenarios

We use a cafeteria room in an office building as test scenario for our routing algorithms (figure 1). For all figures, north points to the top of the paper. The cafeteria measures about 10 by 20 m. It is equipped with two vending machines. Besides the vending machines, the user will find different objects inside the room. In particular, there are different formations of wooden tables along and off the wall, an unusually large metal table in the northeast corner, one ceiling fan along the west and two along the east wall, and a protruding fire extinguisher at chest height in the southeast part of the room. The floor is homogeneously covered with linoleum. We further distinguish between a simple and complex scenario. In the simple scenario, the route calculation operates on an empty room without furniture. The only objects in the room are the vending machines. In the complex scenario, the room is filled with the described objects. These can be classified as obstacles, hazards, clues, and landmarks. We assume that a person enters the room through one of the two doors with the purpose of finding her way to one of the two vending machines.

The designation of landmarks and clues also draws from the discussion of walltrailing. The determination of what constitutes landmarks and clues is based on our assessment of the object's saliency due to its location, shape, and function. We designate all perceivable objects located near the walls as potential landmarks or clues. We posit that the salience of objects increases with the number of characteristic attributes that set these objects apart from all other objects in the environment. The large metal table in the northeast corner is selected as a landmark because of its unique material, shape, texture, and location. All these attributes could be identified by the blind person when following one of the routes. The two doors are considered landmarks due to their common function as home base when exploring new rooms. Additionally, the vending machine along the wall and the three ceiling fans are categorized as clues. The former is easily distinguishable from other objects along the wall but is not unique within the environment. Similarly for each of the latter, the sound of the turning fan blades and the circulated air constitutes a distinct but non-unique stimulus that can be perceived cutaneously and auditorily. Our classification is, to a certain extent, arbitrary since we do not have empirical data as guideline for the selection of clues and landmarks. Most important in this context is, however, that we acknowledge and operationalize the distinction between landmarks, clues, obstacles, and hazards within our algorithm as opposed to relying on a model that only considers a single class of generic objects.

The room contains one hazard, the fire extinguisher. It is classified as such because it is fixed upon the wall at a height that for a typical person would lay above the waist. This creates a threat to the safety of the blind person, because she might not be able to perceive the fire extinguisher through normal cane use. As a result, a route traversing the location of the fire extinguisher at least requires that the traveler be notified of the danger and at most that the route be excluded.

All objects other than the ceiling fans (since they do not impede movement) are also considered obstacles. For the presentation of the proposed indoor routing algorithms in the next section it is important to note that the discussed classification into obstacles, hazards, landmarks, and clues only applies for the blind. In the case of the sighted, the classification is reduced to only one class, i.e. obstacles.

5 Comparison of the routes for the sighted and the blind

5.1 *Implementation*

The indoor routing algorithms were developed with Microsoft Visual Studio .NET and Visual Basic .NET. ESRI's ArcObjects (Environmental Systems Research Institute 2004), a library of objects that serve as the functional foundation for ESRI's line of GIS related products, were used to implement most of the functionality of the indoor routing prototype.

The data model is based on the vector data model in which features of the

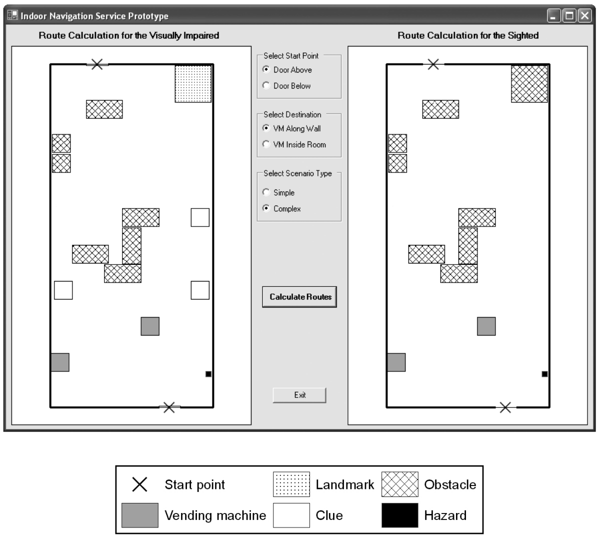

Figure 2. User interface of the indoor routing algorithm prototype.

same geometric type (point, line or polygon) are organized into layers. For each object presented in the scenario description (see section 4), a rectangular feature was created and all objects were organized into polygon feature layers named obstacles, hazards, landmarks, and clues. For computational reasons we introduced a polygon feature layer as representation of the floor of the cafeteria. The walls and doors of the cafeteria were modeled as line features and placed into layers that were named accordingly. A single point feature layer was used to model the two possible start points (i.e. the center of each of the two doors). The route calculation is computed using the centroid of the vending machine as the destination. All layers were stored in a map document file.

Figure 2 shows the prototype that provides the user interface for both algorithms after selecting the complex scenario. The user can switch back and forth between the simple and complex scenario, and select the door to be used as the start point as well as the vending machine to be used as the destination. The route for the blind is displayed in the left frame and the route for the sighted in the right frame. Features with the same texture share the same layer. For instance, obstacles are marked by a crosshatch pattern and the vending machines are gray in both frames. The frame for the blind shows a larger variation of textures because of the larger number of layers. See the legend of figure 2 for a complete overview on the used symbology.

5.2 *Route calculation for the sighted*

The route calculation for the sighted is based on minimizing total travel distance. In the plane, the shortest connection between two given points is a straight line. In the simple scenario, since the room is free from any obstacles, the prototype simply establishes the route by creating a line between the center of the door and the centroid of the vending machine.

In the complex scenario, if there are obstacles intersecting the direct path, the prototype has to find an efficient detour leading the user around the obstacles. The implemented solution for that task is based on the concept of the convex hull. The convex hull of a finite set S of points is the smallest polygon P for which each point of S is either on the boundary or in the interior of P. That is, no other polygon R exists so that $S \subseteq R \subset P$ (de Berg et al. 2000). We use the boundary of the convex hull to construct an efficient detour around obstacles.

All higher dimension geometric objects in the data model (i.e. lines and polygons) consist of points as their building blocks. It is possible to access specific polygonal features, such as the ones representing obstacles, based on their underlying point sets. The prototype checks through topological operators whether the direct line between the start and end point is intersected by any obstacles. If this is the case, then the point sets of all intersecting obstacles are merged and their convex hull is calculated. In order to assure that a sighted person is able to follow the boundary of the resulting convex hull (i.e. walk around all obstacles and return to the start point) without running into obstacles, a 30 cm buffer around the convex hull is added. If other obstacles are detected within this buffer, the point set used for the calculation of the initial convex hull is extended. This process is repeated until the buffered boundary of the convex hull is free from any obstacles, resulting in what we call the corpus of the possible routes, or *route corpus*, for the sighted. Figure 3 shows the route corpus for obstacles that obstruct the direct line between the upper door and the vending machine located off the wall.

The algorithm calculates the projections of the start and end point on the route corpus and uses these to split the route corpus into two parts. The resulting two polylines serve as the framework for the construction of the shortest route. For each polyline, the algorithm iteratively constructs a route by combining straight line segments between the start and end point (as indicated by the user) with the vertices of the polyline (figure 4). During this procedure, possible appendices of the polyline are cut off and the shortest possible route is created. After completing the route calculation for both polylines, the algorithm compares the lengths of the alternative routes and selects the shorter one. Table 1 gives a detailed description of the algorithm in pseudo-code.

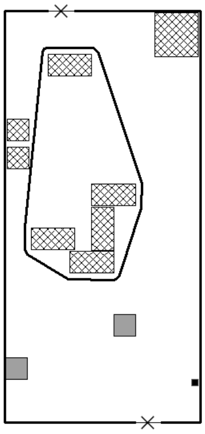

Figure 3. Boundary of the final convex hull (i.e., route corpus).

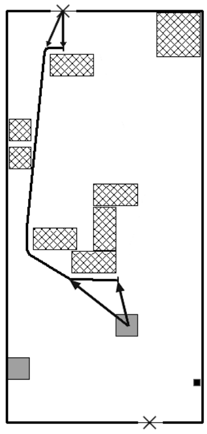

Figure 4. Part of the route corpus and possible connections of start and end point.

5.3 *Route calculation for the blind*

The route calculation for the blind relies on buffers created around the walls and doors towards the inside of the room. The buffer is set to 90 cm, which is in general a suitable value for the shoulder width of an adult male. If the buffer is free of obstacles then the blind person can maintain the full cane sweep while proceeding towards the destination. In the simple scenario, the algorithm checks whether the desired vending machine lies within the buffer. If so, it is possible to access the vending machine solely through walltrailing. Otherwise, the algorithm determines the wall closest to the vending machine and introduces a straight line between them (figure 5). The route corpus is derived by placing a polyline halfway between the points of the inner and outer boundary of the buffer, virtually dissecting the buffer in the middle. The route corpus is then divided into two parts at the point (1) nearest to the start point and (2) nearest to the vending machine. Two alternative routes emerge between the door where the blind person enters the room and the target vending machine. The first trails the walls of the room clockwise and the second counter-clockwise. Since the classification of landmarks, clues, hazards and obstacles is neglected in the simple scenario, length becomes the only measure to assess the quality of the route. Thus, the prototype compares the lengths of the two alternative routes and selects the shorter one.

The complex route calculation for the blind fundamentally relies on the results of the simple scenario. It tests for obstacles that obstruct the simple route and derives a new route segment from a buffer around each detected obstacle. In other words, it creates a route corpus for every obstacle that intersects the simple route. The new route corpi are incorporated into the simple route, replacing formerly obstructed route segments. The final route corpus is shown in

Table 1. Routing algorithm for the sighted.

```
function CALC_ROUTE_SIGHTED(startPnt, endPnt, obstacles, walls)
    route = polyline between startPnt and endPnt;
    blockingObstacles = obstacles that intersect route;
    if blockingObstacles is empty then return route;
    else
        calculate convex hull of blockingObstacles;
        check for other obstacles within 30 cm buffer around convex hull;
        if other obstacles found then
            add obstacles to blockingObstacles, recalculate convex hull, buffer and check again;
            repeat until no new obstacles found;
        routeCorpus = boundary of convex hull;
        project startPnt and endPnt onto routeCorpus;
        split routeCorpus at projected points into firstPart and secondPart;
        adjust orientation of firstPart and secondPart (startPnt → endPnt);
        startConnections, endConnections = empty array;
        for (i = 0, i < #points in firstPart, i++) do
            tmpStartLine = polyline between startPnt and point i of firstPart;
            if tmpStartLine touches firstPart then add to startConnections;
            tmpEndLine = polyline between endPnt and point at index (#points in firstPart
            - 1 - i) of firstPart;
            if tmpEndLine touches firstPart then add to endConnections;
            startConnectionsCount = #polylines in startConnections;
            partialRoutes = empty array of size (startConnectionsCount - 1);
            for (i = 0, i < startConnectionsCount), i++) do
                startConnection = polyline i in startConnections;
                firstPartClone = copy of firstPart;
                while #polylines in firstPartClone != 0 do
                    if end point of startConnection == start point of polyline 0 in firstPartClone
                    then
                        insert startConnection into firstPartClone at index 0;
                        partialRoutes(i) = firstPartClone;
                        break;
                    else
                        remove polyline at index 0 from firstPartClone;
            tmpShortestRoute = shortest polyline in partialRoutes;
            endConnectionsCount = #polylines in endConnections;
            partialRoutes = empty array of size (endConnectionsCount - 1);
            for (i = 0, i < endConnectionsCount, i++) do
                endConnection = polyline i in endConnections;
                tmpShortestRouteClone = tmpShortestRoute;
                while #polylines in tmpShortestRouteClone != 0 do
                    if start point of endConnection == end point of last polyline in
                    tmpShortestRouteClone then
                        append endConnection to end of tmpShortestRouteClone;
                        partialRoutes(i) = tmpShortestRouteClone;
                        break;
                    else
                        remove last polyline from tmpShortestRouteClone;
            shortestRouteFP = shortest polyline in partialRoutes;
        (...) repeat outer for-loop for secondPart to get shortestRouteSP;
        if shortestRouteFP and shortestRouteSP intersect walls then return empty;
        else if only shortestRouteFP intersects walls then return shortestRouteSP;
        else if only shortestRouteSP intersects walls then return shortestRouteFP;
        else return shorter route;
```

figure 6. The two alternative routes are constructed analogously to the simple scenario, differentiating between a destination located along or off the wall.

The selection of the optimal route is more complex than in the simple scenario. It encompasses a trade-off between the length of the route and the number of landmarks and clues that help the blind person orient herself in the environment. The prototype calculates a utility score for both alternative routes based on the count of landmarks and clues along the specific route. Due to the non-availability of a pre-existing trade-off mechanism, we derived our own solution. More specifically, we count landmarks twice and add this number to the single count of clues. In other words, landmarks are assigned

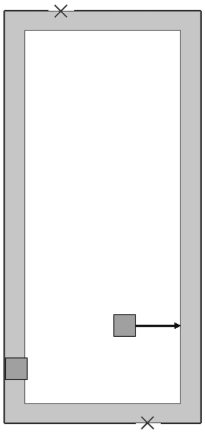

Figure 5. Initial buffer around walls and doors.

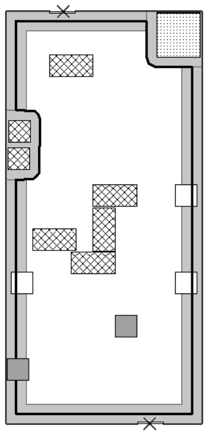

Figure 6. Route corpus derived from buffers of obstacles.

a weight of two and clues a weight of one. The route with the higher score is considered superior as long as its length is less than twice as long as the route with the lower score. Otherwise, the utility score is neglected and the shorter route selected. More formally, the utility score u_r of a route r is given by $u_r = 2 * |L_r| + |C_r|$, where L_r is the set of landmarks and C_r the set of clues along the route. Let r_1, r_2 be the two alternative routes, u_{r_1}, u_{r_2} their respective utility scores and $l(r_1)$, $l(r_2)$ the lengths of the respective routes. The route selection function r_{res} determines the optimal route from the set of possible routes $\{r_1, r_2\}$ as follows:

$$r_{res}(r_1, r_2) = \begin{cases} r_1 \; if \; u_{r_1} > u_{r_2} \wedge l(r_1) < 2 * l(r_2) \\ r_2 \; otherwise \end{cases}$$

This approach not only allows for a trade-off between distance and the count of landmarks and clues, but, by assigning weights, also accommodates for a trade-off between landmarks and clues themselves. A detailed description of the algorithm for the blind is given in table 2.

5.4 *Comparison of routes*

In order to compare the results of the route calculations for the sighted and the blind, we have identified two navigation tasks, one for each scenario. In the simple scenario, the task is to find the optimal route from the lower door to the vending machine off the wall. Within the complex scenario setting, the task is to find the optimal route from the upper door to the vending machine located along the wall. Figures 7 and 8 show the results of the route calculations.

Table 2. Routing algorithm for the blind.

```
function CALC_ROUTE_BLIND(startPnt, endPnt, walls, doors, obstacles, floor)
    initBuffer = 90 cm buffer around walls and doors;
    initBuffer = clip initBuffer with floor;
    divide points of initBuffer into bufferInnerBoundary and bufferOuterBoundary;
    routePoints = empty array;
    for (i = 0, i < #points in bufferInnerBoundary, i++) do
        currentPointIB = point i in bufferInnerBoundary;
        nearestPointOB = point in bufferOuterboundary closest to currentPointIB;
        tmpLine = polyline between currentPointIB and nearestPointOB;
        add middle point of tmpLine to routePoints;
    routeCorpus = polyline consisting of points in routePoints;
    project startPnt and endPnt onto routeCorpus;
    firstRoutePoints, secondRoutePoints = empty array;
    add startPnt and its projection to both firstRoutePoints and secondRoutePoints;
    nearestSegment = segment of routeCorpus that contains projected startPnt;
    add start point of nearestSegment to firstRoutePoints;
    add end point of nearestSegment to secondRoutePoints;
    tmpLine = polyline between last two points in firstRoutePoints;
    if tmpLine contains projection of endPnt then
        replace last point in firstRoutePoints with projection of endPnt;
        add endPnt to firstRoutePoints;
    else
        while firstRouteDone == false do
            tmpSegment = not previously visited segment of routeCorpus that contains last
            point in firstRoutePoints;
            if start point of tmpSegment == last point in firstRoutePoints then
                add start point of tmpSegment to firstRoutePoints;
            else if end point of tmpSegment == last point in firstRoutePoints then
                add end point of tmpSegment to firstRoutePoints;
            if projection of endPnt is on polyline between last two points in
            firstRoutePoints then
                replace last point in firstRoutePoints with projection of endPnt;
                add endPnt to firstRoutePoints;
                firstRouteDone == true;
    firstRoute = polyline consisting of points in firstRoutePoints;
    (...) proceed likewise for points in secondRoutePoints to get secondRoute;
    if 45 cm buffer around firstRoute intersects obstacles then
        blockingObstacles = obstacles that intersect buffer around firstRoute;
        preObstaclesCount = #obstacles in blockingObstacles;
        postObstaclesCount = 0;
        while preObstaclesCount != postObstaclesCount do
            preObstaclesCount = postObstaclesCount;
            for (i = 0, i < blockingObstacles.Length, i++) do
                if 90 cm buffer around obstacle(s) at index i in blockingObstacles intersect(s)
                other obstacle(s) then
                    add intersecting obstacle(s) to obstacle(s) at index i in blockingObstacles;
                    postObstaclesCount = #obstacles in blockingObstacles;
        for (i = 0, i < blockingObstacles.Length, i++) do
            obstacleDetour = boundary of 45 cm buffer around obstacle(s) at index i
            in blockingObstacles;
            obstacleDetour = intersection of obstacleDetour and floor;
            obstacleDetour = difference of obstacleDetour and 45 cm buffer around
            walls and doors;
            split firstRoute between start and end point of obstacleDetour;
            remove segment between start and end point of obstacleDetour from
            firstRoute;
            add obstacleDetour to firstRoute;
    (...) proceed likewise for secondRoute;
    calculate length and clues/landmarks score of firstRoute and secondRoute;
    if score of firstRoute == score of secondRoute then
        return shorter route;
    else if score of firstRoute > score of secondRoute then
        if length of firstRoute < 2 * length of secondRoute then
            return firstRoute;
        else return secondRoute;
```

For the first navigation task in the simple scenario, the routes for the blind and the sighted person start at the center of the lower door. The route for the sighted traveler is a straight line between the start point and the centroid of the vending machine, which is located inside the room. In contrast, the route

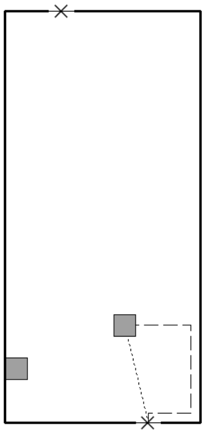

Figure 7. Calculated routes for the simple scenario. The dashed line depicts the route for the blind and the dotted line the route for the sighted. North ↑

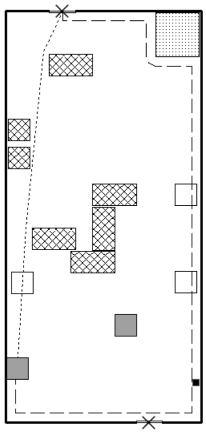

Figure 8. Calculated routes for the complex scenario. The dashed line depicts the route for the blind and the dotted line the route for the sighted. North ↑

for the blind cane traveler takes an immediate right turn, trailing the south wall, before taking a left turn onto the east wall. It continues to trail the east wall until it reaches a point that is even with the centroid of the vending machine. This point represents one end of the shortest line segment that bridges the route corpus and the vending machine's centroid. The resulting route minimizes both the length of the route (in comparison to the clockwise alternative route as calculated by the algorithm) and the length of the route segment that does not allow for walltrailing. In this example, a different alternative route would lead the blind person, starting from the lower door, a few steps left along the south wall and then, after turning right, in a straight line towards the vending machine. This route is indeed shorter than the selected route but its off-wall segment is longer than the one of the selected route. The difference in length of these two off-wall segments might be small, but, at this stage, the route calculation considers only routes that connect to the shortest segment off the wall.

In the second navigation task, situated in the complex scenario, the route for the sighted starts at the upper door. The direct path is blocked by an obstacle located close to the door. Therefore, the route is angled around the obstacle and subsequently straightens out. It then proceeds towards the vending machine that is located along the wall in a straight line until the vending machine is reached. This segment passes underneath the ceiling fan. The total length of the route is 16.3 m. The alternative route for the sighted, which leads the person around the other side of the obstacles, yields a length of 19.1 m. Conversely, the chosen route for the blind trails the walls of the room clockwise. This route has a length of 33.9 m and is therefore longer but less than twice as long than the counter-clockwise alternative with 19 m. It exposes the blind person to three landmarks (the metal table in the northeast corner of the room and both doors) and three clues (the two ceiling fans along the east wall and the vending machine). This results in a utility score of 9, which is higher than the counter-clockwise alternative's 4 (resulting from the start door as landmark, and the ceiling fan along the west wall and the vending machine as clues). Since the chosen route is passing by a hazardous object (i.e. the fire extinguisher in the southeast corner of the room), it is critical to inform the user about the hazard so she can use caution and prevent a collision through self-protection techniques. The prototype therefore gives a warning message subsequent to the selection of the optimal route if that route traverses a hazard.

An overview of the characteristics of the routes and their alternatives for both scenarios is given in table 3. In all cases we observe that the length of the selected route for the sighted is shorter than the route for the blind. With respect to safety, none of the routes for the sighted allow for a minimization of distance that is traveled away from a wall. In fact, none of the routes allow for any kind of walltrailing as the route traverses the interior of the room away from the walls. The possibility of maintaining the full cane sweep is limited to routes where no objects obstruct the direct path between the origin and the destination. Neglecting the importance of walls for the orientation of the blind person and looking at landmarks and clues only, we can say that the only objects suitable for the orientation of the blind person on a route for the sighted (based on our classification) are the starting door and the destination vending machine. Traversing other objects that can serve as landmarks or clues for the blind person is coincidental and occurred once in the complex scenario for the sighted (see previous paragraph). In this case, the route for the blind yields two landmarks and one clue more than the route for the sighted. The aspect of coincidentally encountering objects along the route also holds true for possible hazards and implies further concerns for the safety of the blind person when following a route that was calculated by the routing algorithm for the sighted.

6 Conclusions and future work

In this paper we presented an indoor navigation algorithm for the sighted and the blind. By relying on a two-dimensional data model, the algorithm for the blind calculates routes that incorporate particularities of traveling with the white cane. These were derived from work on O&M. The focus on the actual physical characteristics of traveling indoors with the white cane and the adaptation of a data model that can represent these characteristics distinguishes

Origin and destination of the route		Simple scenario				Complex scenario			
		sighted		blind		sighted		blind	
from	to	sel	alt	sel	alt	sel	alt	sel	alt
upper door	vending machine along the wall	16.1	n/a	18.2	34.2	16.3	19.1	33.9 (9)	19 (4)
upper door	vending machine off the wall	14.3	n/a	23	35.4	15	16.4	22.8 (6)	37.2 (6)
lower door	vending machine along the wall	6	n/a	8.2	44.2	6	n/a	8.2 (3)	46.8 (10)
lower door	vending machine off the wall	4.1	n/a	9	49.4	4.1	n/a	9 (2)	52.6 (10)
		length of route in meters (utility score where applicable)							

Table 3. Comparison of the lengths of the selected (sel) and alternative (alt) routes for the sighted and the blind in the simple and complex scenario. In the case of the complex scenario for the blind the length of the route is followed by its respective utility score in parentheses.

our approach from former approaches of outdoor navigation systems for the blind. More specifically, the presented routing algorithm for the blind enables the calculation of a route that allows for the incorporation of obstacles, hazards, clues, and landmarks into the selection of the optimal route for the blind. These objects impact the safety and orientation of the blind person and must not be neglected.

The differences between the routes for the sighted and the blind are apparent in both navigation tasks. The causes for these differences are twofold. First, the routing algorithm for the blind calculates routes based on the constraints imposed by the physical characteristics of traveling with the white cane. Second, it applies distinct route optimizing strategies that differ from the sighted by trading-off between length of the route and number of landmarks and clues. Based on our discussion of the differences between routes for the sighted and the blind, and the presented implications for safety and orientation of the blind person, we can confirm our hypothesis that a routing algorithm that integrates the principles of indoor cane travel accommodates the information needs of the blind person for orientation and safety as opposed to an algorithm that relies on distance minimization as the only route selection criterion.

We see both outdoor and indoor navigation systems for the blind as possible application areas of the proposed algorithm. In addition, we are interested in applying the algorithm and the principles presented in this paper to (possibly agent-based) models for the assessment of the accessibility of indoor environments for the blind population. A prerequisite to such usage would be the gradual extension of our routing algorithm to more complex environments and navigation scenarios.

Since we could not draw from existing empirical evidence that indicates individual preferences of the blind for the selection of landmarks, clues, obstacles, and hazards in an indoor environment, we strongly suggest to conduct experiments that aim at assessing the suitability of our calculations. We also point out that the presented classification of objects is by no means meant to be fixed. On the contrary, we acknowledge and expect it to be biased by our visual assessment of the objects and the layout of the room, reinforcing the need for experiments on the specificities of navigating without sight in an indoor environment. The most prominent questions in this context are: Which specific properties of an object (e.g. form, location, texture) influence the individual's perception of the object's saliency? What role do salient objects play for the individual's assessment of the goodness of a route? What differences and commonalities exist between the sighted and the blind in terms of their usage of objects for indoor navigation?

Additionally, we propose that efforts should be made regarding the development of technologies that enable the monitoring of indoor environments and objects that are embedded within them. Specific tools that provide a sufficient level of accuracy in built environments do not exist, neither do systems that are capable of tracking the location of objects in a room and update a database if changes occur. A solution in which the objects themselves report changes, allowing for on-demand updates to the feature database, would create a best-case scenario.

Calculating routes on a two-dimensional representation of space is a complex task. The development and testing of the routing algorithms should therefore be continued in order to improve their reliability. One starting point that would improve route calculations for both the blind and the sighted is the incorporation of a detailed analysis of the geometric and topological relationships between encountered obstacles to account for cases where the algorithm might not be able to generate a feasible route. For instance, in the case for the route calculation of the sighted in the complex scenario, the convex hull could extend beyond the room boundaries as new obstacles are encountered. Instead of using a single route corpus, we propose using multiple route corpi derived from clusters of obstacles as future improvement to the algorithm. The clusters would have to allow a sighted individual to walk on the route corpus without bumping into another obstacle (i.e. the buffered convex hulls of the obstacle clusters should not intersect any obstacles or walls). The individual route corpi could then be combined to construct the final route.

Future enhancements of the routing algorithm for the blind should also consider the other possible off-wall segments for the route calculation and compare the lengths of the segments to each other. If, for example, the difference in length between the shortest and the second shortest segment is within a specified range, both should be used to calculate a pair of possible routes. These pairs would then be used to select the optimal route.

In addition, our algorithms work under the assumption that the room in which the route calculation takes place is convex. The walls therefore cannot intersect the route as long as the route does not extend beyond the perimeter of the room. Even though it might be rather unusual for rooms in Western cultures to be non-convex, future versions of the algorithms should incorporate a test for convexity and work for both convex and non-convex rooms.

It is obvious from outdoor navigation systems that landmarks can also be experienced without physical contact, for example, through verbal descriptions. Research in O&M (Hill and Ponder 1976) suggests that knowledge of the location of elevators, stairways, bathrooms, water fountains etc., is important for learning the layout of a building. All these examples could be seen as landmarks that have significance for the development of a mental representation of the whole building. Therefore, landmarks along a possible route should not only be limited to objects that the cane traveler can experience sensorially, but should include all landmarks, either on or off the route, that have significance for the blind. Again, significance in this context depends on user preferences and varies among blind individuals.

A principle similar to walltrailing that was not discussed in this paper is shorelining. Shorelining encompasses the trailing of differently textured surfaces with the tip of the cane and is commonly applied in outdoor travel, for example, when a blind person trails the boundary between a grass strip and the pavement (Hill and Ponder 1976). As such, it has a function similar to walltrailing. Some buildings are constructed so that different types of flooring are arranged in a way that offers navigational information for the blind. Provided that a building offers these extended accessibility features, shorelining may encourage the blind person to venture away from the wall—a case that future enhancements of the prototype should account for.

Finally, we limited our route selection to routes that allow for maintaining the full cane sweep. Other aspects that influence the selection of an optimal route by a blind individual have been neglected. The number of turns on a route or the convenience with which a specific route can be followed could also be considered for the evaluation of the optimal route.

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