Indoor Human Navigation Systems –a Survey

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Abstract

Whereas outdoor navigation systems typically rely upon GPS, indoor systems have to rely upon different techniques for localizing the user, as GPS signals cannot be received indoors. Over the past decade various indoor navigation systems have been developed. This paper provides a comprehensive overview of existing indoor navigation systems and analyzes the different techniques used for: (1) locating the user; (2) planning a path; (3) representing the environment; and (4) interacting with the user. Our survey identifies a number of research issues that could facilitate large scale deployment of indoor navigation systems.

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1. Introduction

Human navigation relies on a combination of mobility and orientation skills [19]. People employ either *path integration*, where they orient themselves relative to a starting position using proprioceptive data, or *landmark-based* navigation, where they rely upon perceptual cues together with an external or cognitive map. Humans may also use a combination of both *path integration* and *landmark-based* navigation [42].

In general, human navigation in indoor and outdoor environments, is performed by measuring the distance and orientation relative to one or multiple reference points. By periodically measuring the displacement and changes

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in the orientation (based on body motion and heading) and adding them with the distance and orientation relative to a reference point, such as a landmark, users can estimate their new location and orientation while navigating in an environment. In case of *path integration* a single reference point is used throughout the navigation, and the location is estimated based on adding all the changes in position and orientation [1]. In this case a map of environment is not needed [43] as the individual keeps track of all the changes. In *landmark-based* navigation, users change from reference points (landmarks) to reference point as they navigate in the environment, considering the relative position of the landmarks. In this case the individual uses a physical or cognitive map of the environment. By recalling the landmarks and their spatial relationships from memory [1], their current position and orientation can be estimated based on the distance and angles relative to one or multiple landmarks [43]. When exploring new environments, path integration is especially useful for exploring new environments where users may build a cognitive map by observing landmarks [46, 62]. Studies [1] show that when maps are available, humans will first navigate using a landmark based approach and as successfully map the environment, switch to using path integration.

Cognitive mapping is concerned with the process in which humans create a mental map of the environment [34]. While navigating many decisions need to be made based on our knowledge of the environment that is stored in the cognitive map. While different senses may be used for navigation, vision is the most effective way for creating a cognitive map, as a great level of details about the environment can be acquired in a relatively short time [5, 32, 58]. While navigating primarily the visual sense is used to recognize landmarks and assess the distance and orientation to landmarks as to be able to associate them with landmarks that are stored in the cognitive map.

In new environments, way finding can be time consuming and may require a considerable amount of attention. This is especially undesirable for emergency crew, such as firefighters or paramedics, as they have to navigate unfamiliar environments on a daily basis often with limited visibility, for example, in case of a fire. Individuals with visual impairments often need the help of sighted people to navigate and cognitively map new environments, which is time consuming and leads to a lower mobility [50]. Individuals with cognitive impairments may have difficulty learning new environments and following directions. Assistive systems for human navigation aim to allow their users to safely and efficiently navigate in unfamiliar environments without getting lost by planning the path dynamically based on the user's location and special needs.

The functionality of a navigation system must include locating and following the user while navigating in the environment. The location can be used for both planning the path and providing surrounding information. As the user's location is known, the system can find a new path in case the user is lost or an alternative path is needed. The planned path is used to generate and provide directions to a user-specified destination. The advantage of using a navigation system to plan a path is that the path can be optimized based on different user requirements, such as shortest path or safest path for individuals with vision impairments. The system interacts with the user to provide directions and surrounding information. Alternative interaction methods can be used in different cases, such as graphical displays to make it easier to follow directions or haptic interfaces to accommodate noisy environment. Since the location of the user is known, such systems can provide information regarding the user's surroundings, such as the location of obstacles or important landmarks.

Over the past decades numerous indoor navigation systems have been developed. This survey paper provides a comprehensive review of technologies used for the different components (localization, path planning, representation, and interaction) of a navigation system. We contrast the different technologies for each component and discuss their benefits and disadvantages with regards to accuracy, cost and usability. Our paper points out several areas for future research, that could help with large scale deployment of indoor navigation systems. This paper is organized as follows: section 2 discusses localizing the user; section 3 planning a path towards a user-provided destination; section 4 creating and representing a map of the environment; and section 5 interacting with the user. Section 6 points out areas for research and the paper is concluded in Section 7.

2. Localization

All navigation systems must include a basic form of localization, i.e., the determination of a user's position and/or orientation. Localization methods can be grouped into four different techniques: (1) dead-reckoning, (2) direct-sensing, (3) triangulation, and (4) pattern-recognition, which are discussed in the following subsections.

2.1. Dead-Reckoning

Dead reckoning localization techniques estimate a user's lo0cation based on a previously estimated or known position. While the user is moving, the dead-reckoning system estimates the user's location through the aggregation of odometry readings. Odometry readings can be acquired through a combination of sensors such as accelerometers, magnetometers, compasses, and gyroscopes [18, 27, 36, 55] or using a user's specific walking pattern (such as the user's average walking speed) [65]. An initial location is typically determined using GPS [27], Radio-frequency identification (RFID) tags [36], or cellular phone positioning [55].

Since the location estimation is a recursive process, inaccuracy in location estimation results in errors that accumulate over time. The accumulated error can be corrected using environmental knowledge [27], RFID tags [36], ultrasound beacons [18], and map-matching [36, 48]. The users' position can be synchronized using direct sensing localization techniques such as RFID tags or pattern-matching localization techniques such as through the recognition of visual landmarks. A benefit of these approaches over direct sensing techniques is a lower installation cost as a smaller number of identifiers have to be installed.

The inaccuracy of dead reckoning and the need to combine it with other localization techniques are the main drawbacks of this method. If a system uses RFID for error correction, the system has all the disadvantages of the RFID localization such as change in the infrastructure and the need for users to carry a RFID reader. If map matching or landmarks are used for error correction, some previous knowledge of the environment is required, which might be costly to prepare.

2.2. Direct Sensing

Direct sensing based localization methods determine the location of the user through the sensing of identifiers or tags, which have been installed in the environment. Two different approaches exist with regard to determining the user's location: (1) location information and information on the user's environment is stored in the tag itself; or (2) this information is retrieved from a database using the tags' unique identifier. Sensing one tag is sufficient for determining the location of the user and tag reader can be easily embedded in hand held devices or in a shoe or a cane [12, 64]. The user's orientation can be determined from relative changes in location from subsequent reads of tags [64]. Five different technologies have been identified that are being used for the tags:

- **Radio Frequency Identifier Description (RFID)** tags are used in most current navigation systems where RFID's can either be passive [13, 37, 64] or active [14]. Some systems use both active and passive tags [12]. Active RFID tags contain a battery and transmit signals automatically. The tags have a larger range, which reduces the number of required tags that need to be installed. The drawback of active tags is the required maintenance, as batteries need to be replaced. Passive tags do not require a battery and are powered to transmit signals by the RFID reader. While passive tags are much less expensive, they have much shorter range and can store much less data [49], which increases their installation cost. RFID tags can be used to store an identifier or location information may be embedded in the tag itself. Active tags can store up to 128kb and passive tags typically store less than 128 bytes [60]. RFID tags themselves are relatively inexpensive [64], but installing them in large environments may be costly, since such tags need to be embedded in floors or walls for users to sense them. For example, if an indoor environment has a carpet floor, installation costs may be low but in the case of concrete or marble floors this may be prohibitively expensive [66]. Another disadvantage of this technique is that the human body can block RF signals [2]. Once installed, tags may be difficult to update, some tags are only readable and they need to be replaced, while others can be updated, but this cannot be done remotely and one has to be within a short distance from the tag. Cheap RFID tags have relative short ranges, which require installing them in an environment with a larger granularity, or else the risk increases that the user will be unable to detect a tag [57]. Active RFID tags have a larger range but they require a power source, such as a battery.

- **Infrared (IR)** localization uses IR transmitters that are installed in known positions where each transmitter broadcasts a unique ID in a cone shaped region [7, 63]. The user carries an IR receiver that picks up data from IR transmitters in range. In some systems, transmitters not only broadcast the position of the user but also provide information about the environment and graphical walking directions [15]. Locating identifiers may be hard, as IR requires line of sight due to their narrow transmission angle [31]. A drawback of IR is that natural and artificial light can interfere with IR [47]. IR systems are costly to install due to the large number of tags that need to be installed [9].

- **Ultrasound identification (USID)** uses emitters that broadcast ultrasound waves with a short wavelength [54]. Emitters are installed in the infrastructure and the user carries a receiver on each shoulder. The flight time difference of the ultrasound signals received from the two closest emitters to each receiver is used to locate the user. By placing a receiver on each shoulder the user's orientation [54] can also be calculated. Other systems have the user carry the ultrasound emitter and receivers are installed in the environment [52] where the users' location is determined centrally. A disadvantage of ultrasound is that walls may reflect or block ultrasound signals [54], which result in less accurate localization. The other drawback of using ultrasound for localization is required line of sight between the receiver and beacons [44].

- **Bluetooth beacons** have been used for localization [29]. For localization, the user has to walk slower than with other techniques because of the device delay [11]. Bluetooth beacons require a power source and henceforth they need to be maintained. Similar to RFID localization, the change in infrastructure is one of the disadvantages of these technique since the receivers or emitters need to be installed throughout the ceiling [24].

- **Barcodes** can also be used as identifiers to localize a user, where users carry a barcode reader. While users are navigating the path, they have to scan the barcodes along the way and they are located based on their unique ID. The system can then provide the user with information about their location, surroundings, and whether they are moving in the right direction [10, 59]. This method is low cost and easy to install and maintain. The problem with this method is that the user has to find each barcode and scan that barcode, which may be cumbersome and will slow down navigation. Users with visual impairments may be unable to use the system as detecting the barcodes relies upon being able to see.

Though most systems use only one type of technique for the identifiers, there exists a navigation system [8] that uses a combination of identifiers, e.g., active and passive RFID tags, or infrared beacons. While using multiple localization techniques might improve the accuracy, the main drawback is the additional equipment that the user has to carry. Particle filters have been used successfully [3, 17] to locate and track users in an indoor environment by combing direct sensing (user as a sensor) and low cost sensors, such as compass.

2.3. Triangulation

Though most direct sensing techniques locate the user by sensing one unique identifier, a number of systems employ multiple identifiers and triangulation to locate the user. These methods locate the user by triangulating the tags installed in known locations. The tags that have been used for indoor or outdoor localization include RFID [2], Infrared (IR) [7], and ultrasound [52, 54].

Triangulation based localization methods use the location of at least three known points to determine the users' location [67]. Lateration uses the distance between the user and at least three known points, whereas angulation uses the angular measurements from at least three known points to the user to determine the users' location [67]. Global Positioning System (GPS) is the most commonly used technique for outdoor localization [16, 22, 28] and uses a trilateration method based on satellites positions to locate the user. GPS receivers analyze a periodic signal sent out by each satellite to compute latitude, longitude, and altitude of the users' position. GPS based car navigation systems can determine orientation based on relative changes in position, whereas handheld GPS systems typically use a compass [26, 51]. For outdoor navigation, GPS has become the standard as it is free, reliable, and it is available in any place on Earth in any weather condition. Using the High Accuracy Nationwide Differential GPS System (HA-NDGPS) an accuracy of locating a user within 10 centimeters can be achieved. Since GPS signals are one-way, it further helps to protect the users' privacy. The main disadvantage of GPS localization is that the GPS signal is not available inside buildings or between tall buildings. There are two alternative triangulation based techniques, which are available in contexts where GPS signals are not available. Cell-tower positioning [4] uses the triangulation of the known locations of cell towers using the provided signal strength of each cell phone tower, whereas wireless local area networks (WLAN) [56, 63] positioning triangulates the location of wireless base stations using the provided signal strength of each station. Both techniques have a lower precision than GPS due to multi path reflection problems [4].

2.4. Pattern Recognition

Pattern recognition based localization methods use data from one or more sensors carried or worn by the user and compare this perceived data with set of prior collected raw sensor data that has been coupled with an environment map. This map of sensor data can be created by sampling at different locations or by creating it manually. Most human navigation systems use a combination of different sensing techniques:

- **Computer vision** based localization techniques [20, 30, 54, 56] require the user to either carry a camera or use a camera embedded in a hand-held device, such as a cell phone. While users navigate in an environment, a camera captures images of the environment, and then by matching the images against a database of images with known location, users' position and orientation can be determined. The camera captures images while the user navigates. Using image matching the users' position and orientation can be determined [35, 54]. A disadvantage of this technique is the high storage capacity required for storing the images that are coupled with the environment map. Significant computing power may be required to perform the image matching [24], which may be challenging to implement on a handheld device. Users are often required to carry supporting computing equipment [20, 54], which may impede their mobility.

- **Signal distribution** or **fingerprinting** localization techniques compare the unique signal data from one or more external sources sensed at a particular location with a map of prerecorded data. This technique requires a training phase, which the received signal strength at different locations are acquired and then stored in a database to create a map. In the next phase, when the user is navigating, the received signal strength or its distribution over time is measured and compared with the map to find the closest match. The signal strength from WLAN (Wireless Local Area Networks) access points [53, 56] is an example of signal distribution localization. An advantage of WLAN signal localization is the relatively small number of base stations that are required for localizing the user [6]. Due to the increased prevalence of wireless

Technique	Methods	System
Triangulation	GPS	AudioGPS [26], Heuten et al. [23], Melodious Walkabout [16], NAVITIME [4], Loomis et al [41], Huang and Liu [28], MOBIC [51], Strachan et al. [61]
	Cell-tower	NAVITIME [4]
	WLAN	OntoNav [63], NAVIO [56]
	RFID	Virtual Leading Blocks [2]
Pattern Matching	Computer Vision	Golding and Lesh [20], Drishti [54], Hub et al. [30]
	Signal Distrib.	NAVIO [56], LaureaPOP [53]
Direct Sensing	RFID	RF-PATH-ID [64], Chumkamon et al. [12], Bessho et al. [8], Ding et al. [14], RG-I [37], RadioVirgilio [13]
	Infrared	Ertan et al. [15], REAL [7]
	Ultrasound	Drishti [54], Cricket [52]
	Bluetooth	UCPNavi [29]
	Barcode	Metronaut [59], Chang et al. [10]
Dead-Reckoning		Koide and Kato [36], Hollerer et al. [27], Nakamura et al. [48], NAVIO [55], Fischer et al. [18], Wu et al. [65]

Table 1: Overview of localization in different systems

networks in indoor environments, often no investment in infrastructure is required as existing base stations can be used [24]. Other signal distribution localization techniques typically rely on a combination of low cost sensors such as an accelerometer, magnetometer (measuring the strength and direction of a magnetic field), temperature, and light sensors [20]. Creating a map for a multitude of sensors is often time consuming and furthermore, the map may not be reliable as some signals such as temperature and light sensors may be subject to daily or seasonal fluctuations [38].

Table 1 shows an overview of the different localization techniques and the different technologies used within each technique.

3. Path Planning

In addition to localizing users, a navigation system can provide directions from the user's current location to a user-specified destination. This involves planning a path and turning it into easy to follow directions. As the user follows directions, the system will dynamically updates its estimation of the user's location and generate a new direction once the previous direction has been completed.

Since the user might fail to follow instructions and veer from the planned path, the system should be able to detect this situation and re-plan the path. Though planning different routes to a destination or dynamically updating the path is a common feature for car navigation systems, only a few human navigation systems [3, 8, 12, 37] offer this feature. Most human navigation systems seem to primarily focus on localization, which allows users to freely explore an environment.

Path planning is an important part of the navigation, which can affect the overall performance of the system. The path needs to be planned in such a way to maximize the usability and success rate while minimizing the chance of the user getting lost. A smarter path planning technique needs to consider users' requirements and customize the path accordingly. Shortest path or shortest travel time is desirable for majority of users and most of the current navigation systems [8, 12, 14] use the shortest path algorithms but this might not be suitable for everyone, for example, tourists might prefer a longer path which takes them along interesting landmarks. A planning technique might minimize the cognitive load [7] considering the complexity of a path and the directions provided, to help elderly or individuals with cognitive problems. For individuals with visual impairments a path that goes along walls reduces the chance of the user getting lost and a path which avoids low ceilings is much safer. Figure 1 illustrates a case where the shortest path results in high uncertainty. Such systems try to find the path with the least hazard [22, 37, 51, 65]. Accessibility of the path might be considered when planning the path for wheelchair users or elderly such that stairs are avoided and the slope of each path is considered [36, 51]. A flexible system might let the user to set preferences based on their needs [4, 36, 51, 63].

Path planning algorithms use graphs or grids to represent the environment. To plan a path using graph based approaches, the environment is divided into sets of nodes and edges connecting these nodes. Depending on the path planning algorithm and constraints, these nodes might be any type

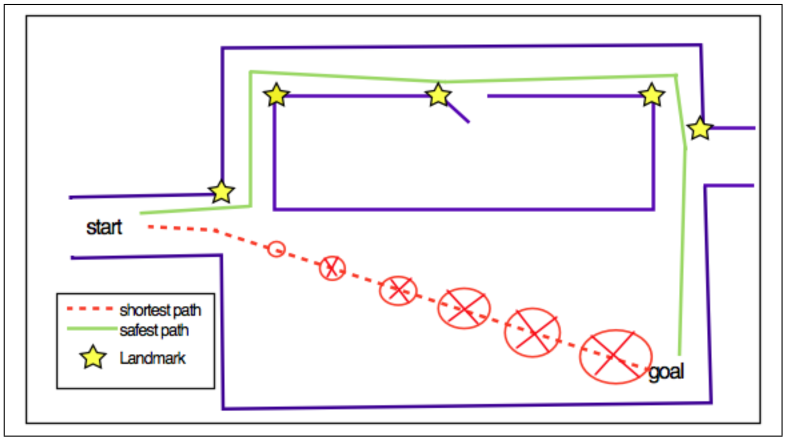

Figure 1: A short path may result in higher uncertainty in localizing the user.

of object, such as hallway intersections, doors, or obstacles. Edges connect these nodes together based on the environment map and if one node is accessible from the other one. In this case each edge might have a weight assigned to it based on different criteria for the path planning. In case of the grid-based approach, the environment is divided to small parts called cells. Each cell contains information regarding the objects at that location and environment description. Cells might have weights associated with them similar to edges in case of the graph based approach. The grid based approach might have a resolution problem, as if the cells are big, multiple object might reside in the same cell and each cell needs to have a structure to hold the details. While using smaller cells increases the computation required for planning a path and many cells might not have any valuable information or an object might reside in multiple cells. A graph-based approach has the advantage of creating the nodes only if there are objects. Edges are created only if objects are accessible from each other, but in complicated environments with many objects, the graph might become big and decreases the performance of the path-planning algorithm. The weight associated with edges or cells play an important role when customizing a path, for example, in case of a path that should avoid stairs, the edges with stairs receive higher weights, or edges with low ceiling have higher weights when planning a path for individuals with visual impairments. Most of current navigation systems use either Dijkstra [27, 36, 39, 45] or A* [27, 51, 65] for path planning.

Table 2 provides an overview of the different path planning techniques used in various systems.

Methods	**Path Criteria**	**System**
Dijkstra	Travel time, avoid stairs, ease of travel	Koide and Kato [36]
	Travel distance	Huang and Liu [28]
	User preference, least hazard	Drishti [22]
	Travel time, Travel distance, safety, ease of travel	MOBIC [51]
A*	Travel distance	Chumkamon et al. [12], Bessho et al. [8], Ding et al. [14], Hollerer et al. [27], Ertan et al. [15], NAVITIME [4]
	Minimum cognitive load	REAL [7]
	Travel distance	Navatar [3]

Table 2: Overview of path planning in different systems

4. Representation

Human navigation systems require storing and retrieving different types of information. The stored information can be used for localization, path planning, generating directions, and providing location information.

Depending on the approach employed by the system, this information may include floor plans, the location and description of objects in the indoor environment, locations of identifier tags or data collected using sensors. This can be a simple two dimensional (2D) map of the environment representing walls and doors with room numbers [27, 36, 63], digital road maps [15, 22, 36, 51], or graph of accessible paths with associated cost for each link [8, 35, 65]. The map can be used for path planning based on the accessible areas or localizing the user. If the system uses a tag based approach to localize the user, tags information is added to the map [13, 14, 64]. Information about landmarks along the path can be added to the map which can be used when providing direction to the user [3, 54, 63, 65]. 2D maps might be the least resource intensive representation and such maps are easy to generate from buildings' blueprints. But adding detailed information regarding objects in the environment and possible hazardous areas, such as low ceilings, to such map might be challenging.

Three dimensional (3D) models can be used to represent the environment [39, 45]. Considerable amount of useful information can be extracted from such models automatically, such as the location of doors, slope of a ramp, or low ceiling. Such models are more expensive to generate but they are language independent and object recognition algorithms can extract information, which helps the system to be deployed globally. 3D models require more storage and processing them for extracting information can be more resource intensive.

The information used by a navigation system is typically retrieved either from a local database [13, 18, 35] or from a central database through wireless connection [2, 8, 53, 63]. Local database approach is potentially more reliable; as they remove the need for a wireless infrastructure to be available, however, any update or change in the physical environment requires changes in all local copies, which results in an inaccurate navigation if local copy is not updated. Storing the information locally might not be feasible for devices with limited storage. Considering the expanding availability of wireless connection with increasing bandwidth, connectivity to a central server might not be a major issue. When the changes in the environment are reflected on the server, clients can have access to the latest representation.

Several navigation systems act as an information system that provides information about the user's surroundings. The information provided varies from providing the name of building and rooms [7, 14] to a detailed description of the room layout including any objects in that room [30, 37, 40, 54] and even the type of door handle and direction in which it opens [64]. This information can be used to help the user to avoid obstacles along the path [13]. This requires storing significantly larger amounts of information than a simple map. The type of information stored depends on the users' needs. While individuals with visual impairments might benefit from detailed information about the direction a door opens, it might be helpful for emergency crew to know the location of the main gas valve in the building, or location of benches for elderly.

Table 3 provides an overview of the different techniques for representing information.

Map	Objects	System
2D	Landmarks, buildings, streets	REAL [7]
	Name of place	Chang et al. [10]
	Empty spaces and objects	RG-I [37]
	Obstacles and surrounding environment	Drishti [54]
	Road markings landmarks	Kaluwahandi and Tadokoro [33]
	Environment information	Huang and Liu [28]
	Object, type of handle, opening direction, distance to objects	RF-PATH-ID [64]
	Tactile landmarks	Navatar [3]
3D	Artwork	Bessho et al. [8]
	Environment and object color	Hub et al. [30]

Table 3: Overview of representation in different systems

5. Interaction

5.1. System Feedback

The three main techniques for providing directions to the user are identified as:

- **Visual:** Providing directions using a display is the most common technique for providing directions. Maps [4, 7] or photos [10] can be displayed and direction can be shown using arrows to the user where to go. Using this method are large amount of information can be provided to the user in a short amount of time. Providing information as such can have a high level of accuracy as realistic images are displayed and arrows can clearly mark the exact location and action the user has to perform next. This method can be beneficial for individuals with cognitive disability as they can directly correspond what they see on the screen with the environment. On the other hand storing real images is storage intensive and downloading them in real time might not be feasible. Alternatively simple text directions [18, 59] can be displayed. Displaying text is far less resource intensive but provides less information, might not be as accurate, and slows down the user.

  3D models of the environments [39] or wireframe model of the user's surroundings and labels of objects [27] can be rendered and displayed to the user. This method might be as efficient as displaying images in interacting with the user and require less storage compared to images but processing power required to render such models is higher.

Having users to look at the screen while following directions may impede their safety as they need to devote their full attention to the screen. Visual interaction might be usable method of interaction with individuals with cognitive problems or tourists but it is difficult or impossible to utilize displays for emergency crew or users with visual impairments.

- **Audio:** Speech based systems [22, 48, 53, 54] use recorded directions [12, 41] or speech synthesis [13, 30, 35] to provide directions to the user. Speech synthesis is much more flexible than the recorded directions and can be performed at runtime without major processing overhead, though recorded directions sound better. Speech based directions are widely used for interaction but they are language dependent. Lengthy speech directions may overwhelm the user and may impede the user's ability to correctly follow the provided direction.

  Because speech directions are language dependent, audio cues can be used as an alternative [16, 26, 28, 37]. Typically some type of sonification or different audio icons with different tones can be used to provide distance information [26]. Audio cues are limited and for many objects no natural audio cue is associated.

  Speech may be safer than using a display as it requires less attention and can be easily facilitated using a headset without impairing the user's normal navigation capabilities and surrounding awareness. Using sound for output reduces the amount of information the user can obtain from the environment. Audio-based output techniques are not suitable when the environment is noisy or when a user is hearing impaired.

- **Haptic:** Haptic based interfaces provide output using the sense of touch and do not interfere with the user's ability to sense their immediate environment using sight or hearing. Textual directions can be provided to the user using a haptic glove approach where users wear six vibration-motors worn on fingers, such as Finger-Braille [2]. Haptic directions can be provided for example by using vibrotactors on a waist belt [23, 64] or in a backpack [15]. Some form of haptification (e.g, changes in frequency and intensity) is used to indicate the angle or distance between the user and the target destination.

While haptic interaction has far less interference with sensing the environment, it requires training and more concentration, as it is less natural to receive complicated information through touch. Haptic-based directions require additional hardware to be provided, which may increase the cost of the system.

As each modality of feedback has some drawbacks, this can be overcome by representing information in multiple modalities. Some systems combine visual and audio [8] or haptic and audio [3, 33, 48, 51] feedback to provide directions to the user.

To navigate the user, the planned path is converted to a set of directions and provided to the user. The type of direction provided to the user may significantly affect the cognitive load; in case the directions are to too long they may be challenging to follow as users feel overwhelmed, where shorter directions may not be as efficient.

Table 4 provides an overview of the different techniques for interaction output.

Modality of feedback	**System**
Haptic	Virtual Leading Blocks [2], Ertan et al. [15], Heuten et al. [23], RF-PATH-ID [64]
Speech	Chumkamon et al. [12], Strachan et al. [61], Nakamura et al. [48], Loomis et al. [40, 41], Drishti [22, 54], RG-I [37], Hub et al. [30], Huang and Liu [28]
Audio cues	AudioGPS [26], Melodious Walkabout [16]
Visual	Metronaut [59], REAL [7] Chang et al. [10], NAVITIME [4],
Visual and Audio	Bessho et al. [8]
Haptic and speech	MOBIC [51], Kaluwahandi and Tadokoro [33] Navatar [3]

Table 4: Overview of interaction output in different systems

Input types	System
Push-button	Nakamura et al. [48]
Keypad	Loomis et al. [40], MOBIC [51], Kaluwahandi and Tadokoro [33], Melodious Walkabout [16]
Speech recognition	NAVITIME [4], Drishti [22, 54], RG-I [37], Huang and Liu [28]
Touch Screen	Navatar [3]

Table 5: Overview of interaction input in different systems

5.2. User Input

Many navigation systems are facilitated using mobile devices where input provision is limited due to small screens and buttons. Some systems use conventional input techniques, such as touch screens [51], keypads [40], and push-button switches [35, 48]. This requires users to hold the device in their hand all the time and look for the button or right place on the screen to press. For emergency crew or individuals with visual impairments interaction as such is not useable. Speech recognition has been widely used [4, 28, 37, 54] to receive user's input, for example for retrieving a target destination to navigate to. This approach requires less user attention and it is more natural. However, ambient sounds in the environment can interfere with the voice recognition system or might interfere with a user having a conversation with someone else. Table 5 provides an overview of the different techniques used for providing input.

6. Research Issues

This survey of techniques used in human navigation systems identified the following research issues:

6.1. Localization

Outdoor navigation systems typically achieve accurate localization at a low cost using GPS. Indoor navigation systems have to rely upon different techniques, as GPS cannot be used indoors. Currently no indoor navigation system has achieved large-scale deployment due to issues with cost, accuracy and usability.

* **Cost:** indoor navigation systems are prohibitively expensive to install as they typically require extensive augmentation of the physical environment to be navigated in. For example, although the cost of an RFID tag is low, installing them at a large scale, such as a campus environment, is often costly. This cost also depends on physical constraints. For instance, if an indoor environment has carpets, installing tags is relatively cheap, but costs increase significantly when an environment has concrete or marble floors [66]. Other techniques require expensive sensing equipment to be carried or worn by the user, for example, cameras and supporting computing equipment may add to the cost of the system significantly [54].

* **Usability:** carrying a multitude of sensors and supporting computing equipment for localizing the user may thwart the usability as well as impede the mobility of the user, which is undesirable especially in the case of users with visual impairments who already carry assistive equipment such as a cane or a Braille reader with them.

* **Accuracy:** while an accuracy of 3 feet is acceptable in most cases for GPS based localization, indoor navigation may require a higher precision. For example, to successfully navigate to a location, an accuracy of 3 feet may not allow for distinguishing between adjacent doors. On the other hand indoor environments are more physically constrained by walls and distinguishable landmarks such as doors and veering becomes less of a problem than for outdoor environments.

For indoor navigation systems to become ubiquitous, their installation cost needs to decrease significantly. Systems that do not require expensive augmentation [3, 30] or that use low-cost, commercially off-the-shelf hardware are more likely to be implemented at a large scale. At the same time, such inexpensive systems need to provide at least as precise localization as their more expensive counterparts. This tradeoff may be difficult to circumvent, but hybrid indoor navigation system could be developed that trade off accuracy versus cost. Low accuracy localization can be used for areas where high precision is not required, such as hallways, where veering is constrained by the physical environment to minimize the installation cost. Large scale deployment of indoor navigation systems lead to greater independence of users with visual impairments and could significantly improve their quality of life [21].

6.2. Path Planning

Many indoor navigation systems are developed for users with visual impairments, who could benefit from "smarter" path planning techniques. Because the identification of tactile landmarks already plays a significant role in how users with visual impairments navigate familiar spaces [5, 32], indoor navigation systems should incorporate this by planning paths that go along easily identifiable landmarks as to increase the successful completion of a path. Though veering is less of a problem for indoor environments than it is for outdoor environments, systems should also avoid large open indoor spaces for users with visual impairments and instead lead users along a wall to assure they arrive at the desired destination. Navigation systems could also plan smarter paths for users with different disabilities. For example, wheelchair users could benefit from paths that do not involve stairs or ramps.

6.3. Representation

Many systems use 2D maps or blueprints to represent the indoor environment to be navigated in. 3D virtual models [30] can be potentially employed to more accurately represent indoor environments with multiple levels and features like low ceilings, ramps, uneven floors and rails, which are impediments to navigation for users with visual impairments. 3D models may be more expensive to create than 2D models, though advances in 3D robotic mapping have reduced these costs significantly. Such models still need to be annotated with addressing information, such as room numbers, or landmarks, such as doors. It is interesting to investigate how to extract landmarks, such as doors or staircases, automatically from the geometry of such models. For indoor navigation systems to become ubiquitous they could leverage crowd-sourcing efforts and offer an open interface to allow for creating indoor models at a large scale. Thousands of 3D models of the exteriors of public buildings have already been successfully created through crowd-sourcing efforts and which can be found on the virtual globe application Google Earth. Models with interior details such as floor plans and doors are becoming increasingly available to be developed to resolve conflicting annotations or to verify the accuracy of annotations.

6.4. Interaction

In addition to issues such as carrying a lot of sensors, which may impede the usability of the system there are a number of other issues to be addressed with regard to interaction design for indoor navigation systems. Interaction using a display [7, 10] may impede safety and using speech [53, 54] may be difficult in noisy environments (such as an airport or theater). Users may also be unable to use a display or audio due to a sensory impairment. Indoor navigation systems must therefore explore more robust forms of interaction, for example, using haptic feedback [15, 23]. A drawback of haptic feedback is that its provision on mobile devices is often limited to a single vibrotactor and prolonged haptic feedback provision may also drain the battery. Most mobile devices currently have touch screens which are inaccessible to users with visual impairments due to their lack of tactile feedback [25]. For example, buttons on more traditional portable devices or on external wireless input devices could be used for navigating an audio menu with possible destinations or common queries. However for blind users it is also important to keep their hands free, since they may already use these to hold a cane. Alternatively input could be provided through the motion sensing capabilities of a portable device as most devices have integrated accelerometer. Users could tilt their mobile device up or down to navigate through an audio menu. Although such type of input would require the user to hold the input device in their hand, it may be possible to integrate an input device in a cane.

7. Conclusion

This paper provides a comprehensive overview of state of the art techniques used in indoor navigation systems for (1) localizing the user; (2) planning a path towards a destination; (3) representing the environment to be navigated in; (4) and interacting with the user. We compare different techniques and discuss their advantages and disadvantages with regard to cost, accuracy and usability. Our paper identifies that indoor navigation systems have not achieved large-scale deployment mainly due to issues pertaining cost, accuracy and usability. The contribution of this paper is that it identifies a number of areas for future research that could lead to large-scale implementation of indoor navigation systems. Future navigation systems need to primarily lower the installation cost, by minimizing the amount of infrastructure augmentation that is required for localizing the user, or by using low cost sensors. Usability needs to be improved by minimizing the amount of sensors users have to carry and providing usable directions in a robust modality of feedback. With regard to path planning, systems need to take into account the users' special needs and plan paths that minimize uncertainty in the localization. With regard to representation, the smallest amount of information needs to be used for localization, path planning, and information about the environment to be navigated in. Tools need to be developed for creating such representations efficiently, while leveraging crowdsourcing efforts. With regard to interaction, a system must accommodate the user's abilities and special needs, minimize cognitive load, and minimize any interference from the environment.

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