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Positioning in Smart Indoor environments for Blind and Visually Impaired Persons

Smart City Project Report

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1 Introduction

While navigating in our day to day doesn't often pose a major challenge, this represents a completely different panorama for individuals who are blind or visually impaired. From dealing with unfamiliar environments to accessing crucial information, the barriers can be arduous. However, technological advancements over the last decades have helped offer promising solutions to enhance the mobility and autonomy of these individuals, many of them focused on outdoor environment but also in indoor spaces where traditional navigation systems turn out to be rather ineffective.

This paper explores the evolving landscape of indoor positioning systems (IPS) and smart interfaces designed to satisfy the particular needs of blind and visually impaired people (BVIPs). By examining the intersection of accessibility, technology, and design, we explore some of the various approaches and challenges in creating inclusive environments and empowering BVIPs to navigate with confidence and ease. From acoustic-based guidance systems to vision-enhanced interfaces, each innovation represents a step towards a more accessible and inclusive future for individuals with visual impairments. Through this search, we aim to learn innovative solutions driving the evolution of assistive technologies for BVIPs.

2 Background

2.1 Needs of Blind and Visually Impaired People

Blind and visually impaired people have to face on their life with a very specific set of challenges given the condition that they have to face. These go from mobility, to social (education, employment and communication).

The presence of visual conditions across our society is more common than we could think. Around 2.2 billion people present a near or distance vision impairment, according to the World Health Organization (WHO), it is not a condition to which certain group of our society is subject as it is distributed across all ages with a slight increase with those over 50 years and represents an important economic impact with an estimate annual global productivity loss of about US$ 411 billion purchasing power parity.[1]

Within the major challenges that they have to face, accessibility and mobility represent challenging tasks. There's an effort within society to try to turn the environments more friendly, by deploying infrastructure within buildings, sidewalks and public spaces transportation systems, such as diverse applications as screen readers, Braille displays and tactile maps which are not enough given that the capability of navigating with autonomy and safety is not a simple task. Pedestrian infrastructure such as tactile paving and audible signals have been implemented and seek to aid people, yet the use of mobile devices nowadays are key for solutions such as GPS, which works well on outdoors, however inside a building is not a feasible option.

2.2 State of Indoor Positioning

Global Positioning Systems (GPS) is one of the most popular positioning and navigation systems to locate any receiver on a real-time basis [2]. It works by having a constellation of satellites which broadcast ranging information to help a passive receiver calculate its precise latitude, longitude and altitude in real-time. This positioning information is used for geographical navigation by civilians and military alike. However, GPS (and similar technologies such as GLONASS) are inaccurate for indoor positioning and navigation as the receiver has to be in line of sight with the satellite [3]. Indoor positioning systems replace GPS and similar technologies for way-finding in indoor spaces of public/commercial interests such as malls, warehouses, airports and public libraries [4].

Any indoor area or location can be uniquely identified by one or more combinations of its environmental characteristics like the presence of a particular Wi-Fi router, its distinct arrangement of walkable/accessible areas, spatial features, ambient light and sound etc [5]. Most indoor positioning systems leverage these characteristics to build a curated set of data and associate it to that particular location. Individuals can be located in this space by correlating sensor information from their devices to the training data of the indoor locations [4].

Subsequently, indoor positioning systems lack in positioning accuracy if the training data is faulty, or becomes irrelevant over the time, or noise in the environment obscures the actual signal from the sensors.

A robust approach is to come up with an indoor positioning system which fuses sensory information from various sources such as Wi-Fi/Bluetooth access points, Ultra Wide Band systems, spatial vision, and ambient light so that the noise in one of the sources can be compensated by signals from the other source [6].

2.3 Smart environments

The integration of indoor positioning systems (IPS) along with smart environments can potentially can revolutionize the navigation experience for visually impaired and blind individuals. By leveraging the precision of IPS technology, users could receive customized and real-time navigation assistance within complex indoor spaces like malls, airports, or offices. Through auditory signals, tactile feedback, or voice assistants, smart environments can provide personalized directions that customize to user preferences and needs. These systems could also have the possibility to offer real-time alerts about obstacles or changes in the environment, ensuring safe and efficient navigation. Integration with wearable devices such as smart glasses or haptic feedback devices further enhances accessibility by delivering navigation assistance directly through these devices. Moreover, IPS integration extends beyond public spaces to smart homes, empowering visually impaired individuals to navigate their living spaces more independently.

This integration seeks social inclusion by enabling greater participation in social activities or work environments, for example. Additionally, the data collected from user interactions and navigation patterns can drive continuous improvement, refining the navigation experience over time. Overall, the integration of IPS with smart environments holds tremendous promise in improving the mobility, independence, and quality of life for visually impaired and blind individuals.

3 Indoor Positioning System (IPS)

3.1 Approaches to IPS: Radio based vs Visual

With the advent of smartphones with high quality camera the research related to vision based positioning systems has been split into two major approaches. The first approach is using pure visual capabilities from a digital camera with an embedded complimentary metal oxide semiconductor image sensor (CMOS) [7]. This approach can be further divided into active and passive positioning systems. In active visual positioning systems, the users (with their smartphone cameras) locate themselves by correlating current image/video frames from their cameras to an existing set of curated images/videos of that particular location. For locations where its infeasible to create this curated set of images/videos, these locations may require special light emitting diode lamps (LEDs) which can transmit their position encoded via light pulses [8]. The approach assumes that the camera mainly rotates in the yaw plane, and the camera is in line of sight with the LED lamps. These assumptions breaks down in real-life where the users typically rotate the camera to their convenience. Moreover, the location requires to fit these special LED lamps which need to broadcast their identifiers (IDs) all the time. Passive positioning systems mainly leverage existing mesh of security cameras to capture images of the people, perform face detection and face recognition and track movement of each detected face [9]. This technique assumes availability of high quality security cameras for image/video processing (resolution of 1920 X 1080 pixels, 1080p). Moreover, performance for face detection and recognition by security cameras deteriorates when a face of a person is occluded due to a crowded environment [10]. This makes is unsuitable for places with high footfalls such as malls, retail spaces, stations etc.

3.1.1 Radio Based Positioning System with fusion

The second major approach entails fusing position data from computer vision with another position data from a combination of IoT devices to some mitigate issues above. These IoT devices can be radio waves emitting devices such as Wi-Fi, bluetooth beacons(BLEs), UWB transceivers etc. Alternatively, the IMU sensors from smartphones can also be used to perform positioning based on dead reckoning of the user [11]. First, positioning based on received signal strength (RSS) fingerprinting from Wi-Fi/BLEs are often susceptible to multi-path effects in indoor environments with obstacles [12]. Subsequently, the RSS map data has to be constantly refreshed with the current environment to maintain its accuracy. This is impractical in real life. Second, as the time progresses, positioning from IMU sensors suffer from moderate levels of drift and bias due to noisy readings [13]. Third, an implementation by fusing computer vision and IoT based positioning systems can result in a highly accurate localization [14, 15, 16, 17], but each of the implementation suffers in a crowded environment. Moreover, the experiments assume the area of interest to be on a single floor instead of multi-level buildings. The approaches struggle to localize in real-time due to high computational complexity, or require additional topographical data (such as detailed floor plans) to model navigable areas.

3.1.2 Technology Comparisons

As seen before, IPS can largely be split into several technical implementations. IPS which use 2.4GHz Radio based waves are typically implemented utilizing the existing Wi-Fi routers/access-points or by deploying special Bluetooth Low Energy (BLE) Beacons. Ultra Wide Band (UWB) technology is an upcoming IPS implementation which mitigates the issues faced by 2.4GHz IPS implementations such as radio interference/reflection and promises to be more accurate [18]. Just using GSM towers (or cell tower map) trilateraltion can be a cheap and effective way of obtaining coarse positioning, though not practical for indoor purposes. Using IMU Systems with dead-reckoning maps is alternative implementation which doesn't rely on any availability of Radio or Visual cues.

Each implementation faces its own set of challenges, which can be categorized either as a physical challenge, which is the inherent limitation of the chosen technology or practical challenges, which are the limitations encountered when a large scale deployment is required. They can be summarized in table illustrated in figure 1.

		WiFi	**BLE beacons**	**UWB**	**Cell tower map**	**Dead reckoning with Accessibility Maps**
	Accuracy	2-5 metres	1-2 metres	< 1 metre	5-10 km	2-5 metres
Key differences	**Requires external hardware**	F	T	T	F	F
	Affected by low quality signal emitters - RSSI variation	T	T	T	F	F
	Affected by low quailty signal receiver	T	T	T	F	F
	Temporal variation in RSSI data - short time temporal variation (body effect, RSSI) - long time temporal variation	T	T	Partially True	F	F
Physical challenge	**Affected by noisy IMU sensors - Magnetometer for heading - single axis gyros**	F	F	F	F	T
	Significant Android battery consumption	F	F	NA	F	T
	Requires modeling physical space - Effort vs Accuracy creating topographical data	NA	T	T	F	T
	Works with limited computing power on devices	T	T	NA	T	F
Practical challenge	**Hardware maintenance**	F	T	T	F	F
	Needs Android location permission	T	T	NA	F	T

Figure 1: Technology Comparison on Physical and Practical Challenges

4 Smart Interfaces

4.1 Challenges in Designing Interfaces for BVIP

Designing assists and aids for visually impaired persons is a challenging and ambitious research area. Engineers and designers provide systems in order to allow blind people to navigate freely and independently. Before technology, blind people relied on the help of guide dogs which require extensive training and high cost. Moreover, the white cane could not help them navigate either indoors or outdoors because of the lack of details provided. The problem of indoor navigation remains largely unsolved. Critical aspects should be always taken into consideration: sensing the environment and informing the blind user. Detecting the environment can be done with several sensors (ultrasonic, infrared, pressure, etc.), or cameras. Audio messages or tactile senses are used to inform the user. [19]

When it comes to navigating in the physical world, the scenario is more complex; in fact, navigating independently in unfamiliar environments is nearly impossible for someone who does not pick up much of the contextual, mostly visual information provided by the environment. For instance, if a person found him/herself in a random building, a quick glance around the current location tells a lot already about the building. Things such as signs, furniture, corridors and staircases, and the view from windows can tell about the purpose of the building, and a location can be approximated from the outside view. Most of this information will be completely missed by someone who cannot pick it up with the eyes, and so a major challenge is to design a system that can transmit this information, or provide the knowledge in another way. This underlines the importance of developing advanced navigation aids that can interpret and convey this crucial contextual information to visually impaired users. [20]

Building on this foundation, there are multiple challenges for mobile indoor assistive navigation: the inaccessibility of indoor positioning, the immature spatial-temporal modeling approaches for indoor maps, the lack of low-cost and efficient obstacle avoidance and path planning solutions, and the complexity of a holistic system on a compact and portable mobile device for blind users. The advancements in computer vision software (such as visual odometry) and hardware (such as graphics processing units) in recent years have provided the potential capabilities for vision-based real-time indoor simultaneous localization and mapping (SLAM), indicating significant progress in addressing these challenges. [21]

At the conceptual level, any novel, visually impaired-dedicated assistive device should focus on the development of various orientation strategies, including spatial models/surface mapping, in order to adapt the user to unpredictable conditions that can arise during navigation. However, in novel, unknown environments, the visually impaired user faces a set of difficulties and suffers from insecurity or anxiety. In recent years, various research works have addressed such challenges in their attempt to gain a higher level of understanding of the surroundings, to increase cognition, and to facilitate the navigation of visually impaired people in both indoor and outdoor environments. Most of the existing assistive technologies incorporate functions for obstacle avoidance and route selection. Because most partially sighted or blind people live in developing countries, the assistive device should be both relatively affordable, from a financial point of view, and easily available. [22]

In fact, another crucial challenge is to provide a convenient mechanism to handle system input and output for visually impaired people. Typical navigation systems assist such people through voice prompts. For example, Microsoft's Seeing AI application analyzes video footage captured by a smartphone and sends verbal commands to the user for guidance. In practice, it is difficult for a voice prompt to keep up with changes in a scene in a continuous manner. It takes a whole sentence for a voice prompt to describe a static scene. Hence, when a person is moving, verbal cues will not be able to pass sufficient information in real time without hampering the mobility of the person. Besides, the machine-generated voice prompt interferes with the natural communication activities of the user, highlighting the need for more innovative solutions that can provide real-time, effective guidance without compromising the user's ability to interact with their environment. On top of that, visual restriction limits the possibility to read the input from a user. Most of BVIPs won't be able to use a smartphone to type in the navigation parameters. As a result, there is a need to deploy a system that overcomes this problem. [23, 24]

Finally, depending on a level of impairment, a person may operate different kinds of devices: high-contrast smartphones, control buttons, voice readers etc. If the system is designed to satisfy the needs of people that use only one of the listed devices the others won't benefit from it. Given that the goal of our research is to offer a solution that grasps as many people as possible, we will try to address the challenge of making the system flexible and adaptable ensuring accessibility. [25]

4.2 Different approaches to building Smart Interfaces

4.2.1 Acoustic smart interface

One of the proposed solutions in this area is a sight-to-sound human-machine interface (STS-HMI), a novel machine vision guidance system that enables visually impaired people to navigate with instantaneous and intuitive responses. The proposed STS-HMI system extracts visual context from scenes and converts them into binaural acoustic cues for users to establish cognitive maps.[23] Human hearing perception can locate and unravel multiple sound sources. One can achieve such cognitive ability by analyzing interaural time differences (ITDs) and interaural level differences (ILDs) of sounds . [26]ITDs represent the difference between the arrival time of the same sound in both ears. ILDs represent the difference in the loudness of the sounds. By manipulating these two acoustic cues, a system can guide human perception with the location of a sound source. For example, surrounding sound technologies such as DTS (dedicated to sound) can create an immersive movie experience by mimicking the spatial arrangements of sound sources in a movie scene. By manipulating the quality of sounds generated by the speakers, these technologies enable audiences to identify a sound source's location intuitively. The proposed STS-HMI system relies on human perception for sound source localization. Moreover, through training, visually impaired individuals can develop a more sensitive sense of hearing and sound source localization . [27]

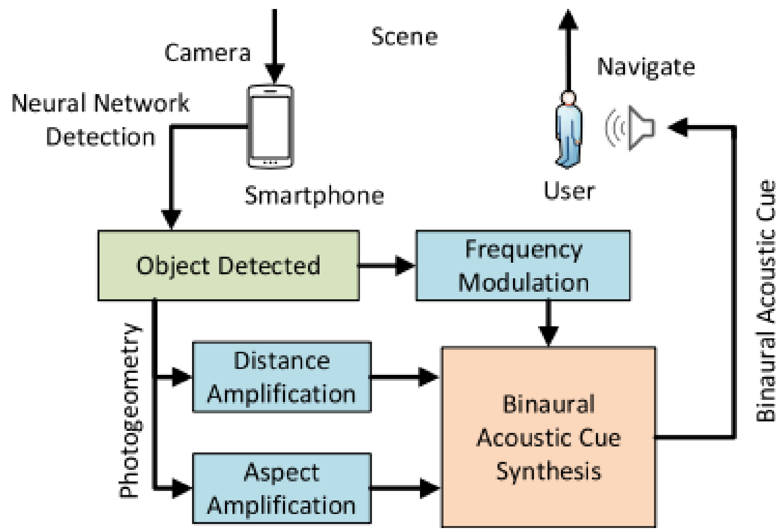

Figure 2: Design of the proposed acoustic-based user interface. [23]

To create intuitive acoustic cues for navigation, the human-machine interface needs to encode the location and the aspect of each object by manipulating the loudness and the frequency of the acoustic cue. Based on this principle, an acoustic-based human-machine interface can be created. Such a system enables visually impaired users to visualize the context of their surroundings conveniently in real-time. Once the user's surroundings have changed, the binaural acoustic cues are triggered to inform the user.

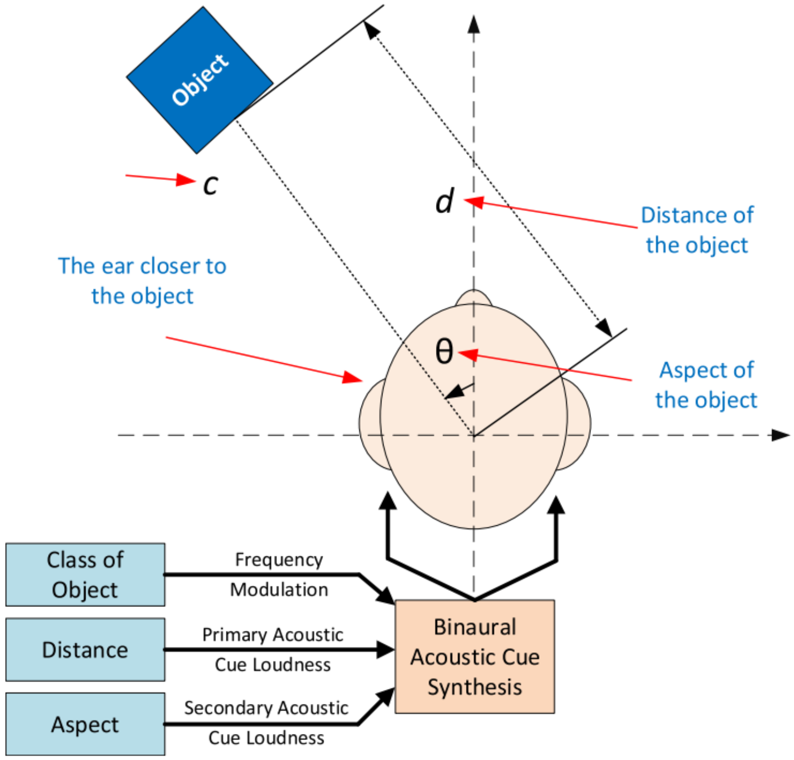

Figure 3: Top-down view of objects relative to the user.[23]

Thus, users can be updated with their surrounding environment as if they can see. Two attributes are defined for encoding the information describing an object in a scene: (i) the frequency associated with the class of the object and (ii) the loudness associated with the distance and the aspect of the object. As shown in Fig. 2, the human-machine interface chooses the frequency of binaural cues based on the class of the object c. Then, the ear closer to the object receives the primary acoustic cue corresponding to the distance d, and the other ear will receive the secondary acoustic cue corresponding to the aspect theta. The following sections explain how navigation instructions are encoded in the binaural acoustic cues. [23]

4.2.2 Vibration based interface

Here we can see a few different solutions as well which we will dive deeper into: The design and implementation of a Radio Frequency Identification (RFID) and Global Positioning System (GPS) integrated navigation system, named Smart-Robot (SR), is aimed at operating in both familiar and new environments. This innovative navigation system assists visually impaired people by enabling them to leave their homes independently in a safe and convenient manner, and participate in more social and civic activities to improve their quality of life. At the same time, the development of a reliable aid system for the visually impaired symbolizes a civilized, harmonious, and progressive society, representing a service-oriented project for engineers. The Smart-Robot is a navigation assistant for visually impaired individuals that integrates RFID and GPS localization technologies. It facilitates navigation in both indoor and outdoor environments, assisting users in reaching predefined destinations. Feedback to the user is provided through acoustic messages and vibration patterns, which are transmitted via a hand-mounted glove, thus ensuring that the system is both effective and user-friendly. [22][28]

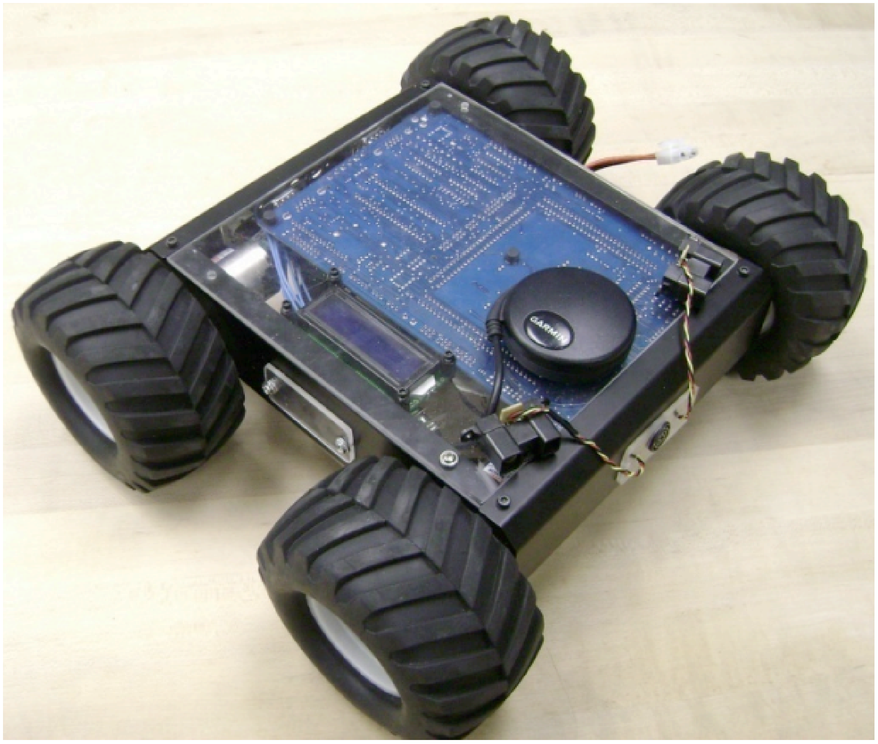

Figure 4: Smart-Robot Chassis .[28]

Another solution worked on is a low-cost augmented reality (AR) system for blind and partially sighted people. The framework, called Arianna, is designed to identify a safe walking path in indoor spaces. At the hardware level, the system is based on a video camera integrated on a smartphone device. The user feedback is transmitted with the help of a set of vibration patterns. The walking path is determined using a set of interests points, indicated by QR codes or by following a path painted on the floor.[22]

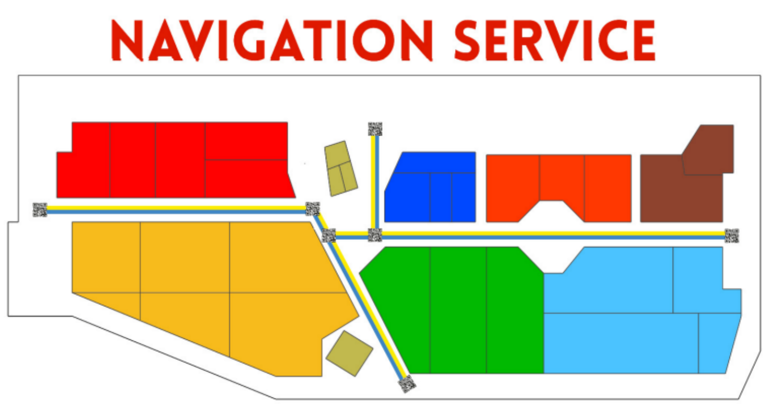

Figure 5: Example installation of the ARIANNA system. .[29]

Another approach focuses on the development of an Intelligent Situation Awareness and Navigation Aid (ISANA) system, paired with an electronic SmartCane prototype. The aim is to offer a comprehensive solution for indoor navigation assistance. Utilizing the tablet as its mobile computing platform, the system represents a significant advancement in the field, blending innovative technology with practical application for enhancing the mobility of visually impaired individuals.

The proposed ISANA system runs on a mobile device, which has an embedded RGB-D camera providing depth information, a wide-angle camera for visual motion tracking, and a 9-axis inertial measurement unit for visual-inertial odometry. The physical configuration of this includes a tablet, a frame holder, and a SmartCane which outfits a keypad and two vibration motors on a standard white cane. ISANA provides indoor wayfinding guidance for blind users with location context awareness, obstacle detection and avoidance, and robust multi-modal HMI. [21]

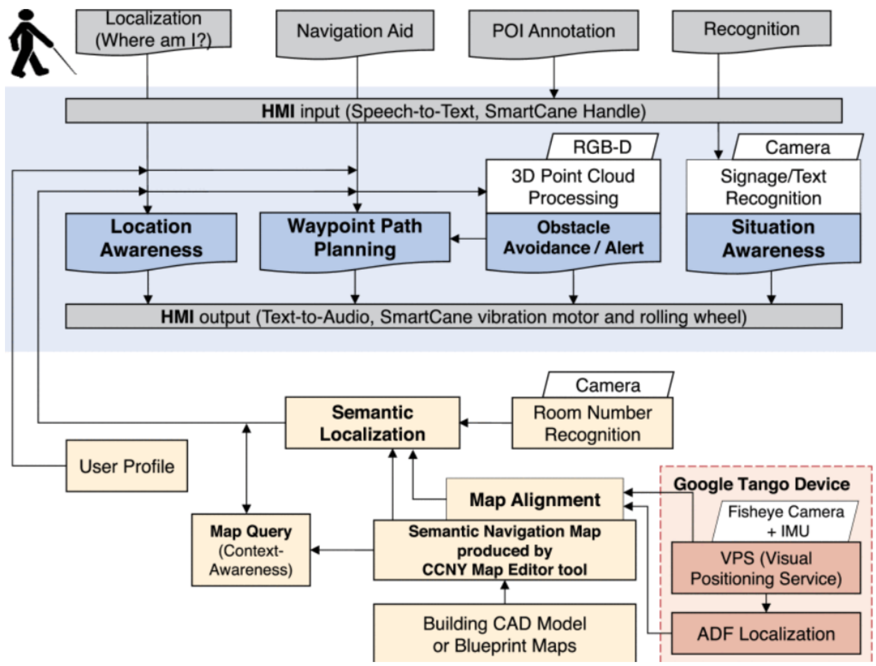

Figure 6: . ISANA system functional block diagram. [21]

Here the VPS and ADF for ISANA assistive navigation have been leveraged. Fast retina keypoint visual features are extracted from the wide-angle camera for six degrees of freedom (DOF) visual odometry (VO), which is fused with IMU for visual-inertial odometry (VIO). The visual feature model is stored in ADF for loop closure detection so that the accumulated odometry drift can be suppressed. [30]

4.2.3 Adapted indoor navigation with the help of QR-Code and RFID

When we are talking about a visually impaired person we not necessarily mean a blind person. This section describes a navigation system that tries to address the challenges that emerge when we try to adapt it to the people with different level of visual impairment.

Why would we even need to adapt the system? Well, the answer is simple: the sighted and blind people do not possess the same equipment to help them deal with the navigation. The proposed solution considers the case when sighted people have a specially designed smartphone with increased level of contrast that help them access its basic functionality. On the contrary, a fully blind person can not use this type of technology, instead, they make use of a specific mobile reader to detect a signal from RFID tags in order to direct them inside the indoor environment. [24]

The idea of the system is simple. We assume that so-called tags are spread throughout the building. Tags can be of 3 different types:

- Boundary tags - used to determine the general map of a building facilitating navigation, obstacle avoidance and shortest path computation.
- Information point - describe general information about the environment: name of the building, floor, sector etc.

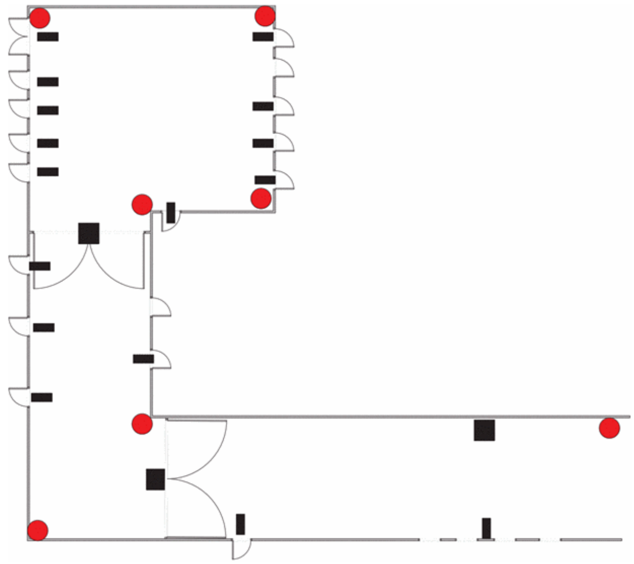

Figure 7: Tag distribution throughout an indoor environment. Red circles - boundary tags, squares - information points, rectangles - points of interest. [25]

- Point of interest - used to identify a particular indoor location.

First, when a user wants to reach a particular destination they give an input via the available device (microphone or smartphone). After, the system computes the shortest path avoiding obstacles and leading through the way point tags. These tags serve as guides carrying useful information about the particular location (Point of interest and Information point tags) thus enhancing navigation and giving a visually impaired person more insight on the environment. Each of the tags is physically represented by both: a RFID tag and a QR Code (Quick Response Code). While RFID tags are read by the mobile devices owned by blind people, QR Codes require special software installed on a smartphone that perform the function of QR Code reader and the information display stored on it. The details of the implementation of the software are not strictly fixed and may vary from one system deployment to another. [25]

4.3 Comparisons and design considerations

As we were able to contemplate in this section, the range of possibilities to deploy a navigation system for visually impaired people is quite large. A lot of research workers spend their time in order to provide a universal solution embracing all the requirements. Nevertheless, such scenario is hardly possible due to the complexity of design, expensive deployment, system parameters that sometimes are contradictory etc. Hence there is a big interest to integrate the technologies, ideas and techniques in such way that all together they would give the most profit for the end user and would be feasible to implement. Such non-trivial task requires analysing both advantages and disadvantages of the already integrated approaches and outlining the areas of improvement.

To start with, let's consider acoustic smart interface. STS-HMI system on paper gives a lot of benefits making the information exchange concise and relatively efficient. To recall, the model relies on neural network object detection where the input data is captured by the camera of a smartphone and is fed to the NN. Here we come back to the affordability problem: a user needs to have a smartphone with a high computational power being able to analyse the digital environment in a real time, let alone the camera that has to provide decent quality of video record. Given that most visually impaired individuals do not have a wealthy background this can become a real problem. On top of that, having a smartphone as an input device may significantly limit accessibility of a system since a fully blind person per usual do not possess it. This enforces additional considerations about integration of a new input device into the system. [23]

Continuing the general idea, probably the biggest challenge for BVIP navigation is to find an acceptable balance between the cost and the accuracy of the output. Taking into account the example of ISANA where the input can be given in multiple forms, the system consists of a diverse technological stack creating a risk for some features to become redundant keeping the price increased. While matching proposed technologies against each other all of them show high precision in perfect conditions but it is a big question how the system would perform had the hardware part was changed. On the other hand, more cheap setup with RFID tags (especially non-active ones) and way points shows worse performance and give precision around 80%. [25]

At the same time, another problem is clearly illustrated in Smart-Robot solution with vibration based interface. The idea of having a robot that leads a visually impaired person from place to place is great, however the question is how long such set up will remain autonomous. The fundamental principle of a smart navigation is to make the life of visually impaired people more convenient so if they would have to come back home and change the battery every second hour this condition will not be met. Same restriction emerges in case of STS-HMI and ISANA because constant data collection via camera along with the image processing consumes a lot of energy. [28]

Final remark is that the idea of deploying mentioned systems should be tightly coupled with the concept of accessibility. It is strongly recommended that the system would provide ways to navigate using various technologies. As described in part 4.2.4, the way point tags are represented by RFID tags and QR Codes. This set up may be extended even further by enabling support for a tablet or augmented reality.

5 Future work

It is obvious, that there remains a lot of work to be done in the area. All of the proposed solutions have some form of knowledge gap that needs to be filled, to be able to better satisfy the needs of BVIP.

For the indoor positioning systems, the LED solutions can perform optimally but in some cases, error can be up to 200mm, and that is something that needs to be dealt with. From a more general standpoint, the positioning accuracy of the various models needs to be improved (by improving the accuracy of the step size of the PDR for example. [11]

For the STS-HMI system, four areas need to be studied further; how to improve the range and accuracy of object detection and localization, integration with additional navigation methods, the possibility to incorporate environment familiarisation techniques which can help users, and most importantly, future studies of binaural acoustic cues for scene analysis and navigation can be extended to include information encoded in pitches since human ears are also sensitive to pitch changes and time differences [31].

In the case of Intelligent Situation Awareness and Navigation Aid (ISANA), future research directions will focus on cognitive understanding and navigation in more complex and cluttered environments, such as transportation terminals.

Usability of the QR-Code and RFID based solution has not been evaluate using BVIP and as such, it is difficult to quantify its efficiency at this point. The same can be said of the ARIANNA system on which more tests need to be conducted to evaluate the performance (reactivity, intensity and type) of the vibrational cues.

Another factor that needs to be considered, is how to reduce the potential invasiveness of the vibrational sensors as they require an actual physical contact with the subject. In addition, the main limitation of haptic devices is related to its low resolution capability. For this reason, the tactile interfaces are only suitable for limited information feedback. As indicated in [32], the majority of blind and visually impaired people prefer the speech interface when using a navigation assistant. It would be useful to find an effective way to combine some of these feedback methods and perform a comparison of the various methods, based on user feedback.

References

[1] World Health Organization. Blindness and vision impairments - key facts, 2023. URL `https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment`.

[2] Bradford Parkinson, James Spilker, and Gabriel Elkaim. *Global Positioning System (GPS)*. John Wiley & Sons, Ltd, 2003. ISBN 9780471263869. doi: https://doi.org/10.1002/0471263869.sst069. URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/0471263869.sst069`.

[3] Paul A. Zandbergen and Sean J. Barbeau. Positional accuracy of assisted gps data from high-sensitivity gps-enabled mobile phones. *Journal of Navigation*, 64:381 – 399, 2011. URL `https://api.semanticscholar.org/CorpusID:56090219`.

[4] Jayakanth Kunhoth, AbdelGhani Karkar, Somaya Al-Maadeed, and Abdulla Al-Ali. Indoor positioning and wayfinding systems: a survey. *Human-centric Computing and Information Sciences*, 10(1):18, May 2020. ISSN 2192-1962. doi: 10.1186/s13673-020-00222-0. URL `https://doi.org/10.1186/s13673-020-00222-0`.

[5] Cyril Ray, Fabrice Comblet, Jean-Marie Bonnin, Yvon-Marie Roux, and Franc Peyret. *Combining accurate geolocalisation, mobile wireless technologies and information systems for location-based services.* 01 2009.

[6] Xiansheng Guo, Nirwan Ansari, Fangzi Hu, Yuan Shao, Nkrow Raphael Elikplim, and Lin Li. A survey on fusion-based indoor positioning. *IEEE Communications Surveys Tutorials*, 22(1):566–594, 2020. doi: 10.1109/COMST.2019.2951036.

[7] NASA. NASA Spinoff 2017: Flight-Proven Tech. `https://spinoff.nasa.gov/Spinoff2017/cg_1.html`, 2017. Accessed on March 21, 2024.

[8] Md. Shareef Ifthekhar, Nirzhar Saha, and Yeong Min Jang. Neural network based indoor positioning technique in optical camera communication system. In *2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, pages 431–435, 2014. doi: 10.1109/IPIN.2014.7275513.

[9] Lien-Wu Chen, Chi-Ren Chen, and Da-En Chen. Vips: A video-based indoor positioning system with centimeter-grade accuracy for the iot. In *2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, pages 63–65, 2017. doi: 10.1109/PERCOMW.2017.7917523.

[10] Christopher Nielsen, John Nielsen, and Vahid Dehghanian. Fusion of security camera and rss fingerprinting for indoor multi-person tracking. In *2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, pages 1–7, 2016. doi: 10.1109/IPIN.2016.7743630.

[11] Yuqin Wang, Ao Peng, Zhichao Lin, Lingxiang Zheng, and Huiru Zheng. Pedestrian dead reckoning-assisted visual inertial odometry integrity monitoring. *Sensors (Basel)*, 19(24):5577, Dec 2019. ISSN 1424-8220. doi: 10.3390/s19245577. URL `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6960658/`. PMID: 31861161.

[12] Israat Tanzeena Haque. A sensor based indoor localization through fingerprinting. *Journal of Network and Computer Applications*, 44:220–229, 2014. ISSN 1084-8045. doi: https://doi.org/10.1016/j.jnca.2014.06.001. URL `https://www.sciencedirect.com/science/article/pii/S1084804514001313`.

[13] Paul D. Groves. Principles of gnss, inertial, and multisensor integrated navigation systems, 2nd edition [book review]. *IEEE Aerospace and Electronic Systems Magazine*, 30(2):26–27, 2015. doi: 10.1109/MAES.2014.14110.

[14] Jichao Jiao, Fei Li, Zhongliang Deng, and Wen Liu. An indoor positioning method based on wireless signal and image. In *2016 9th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI)*, pages 656–660, 2016. doi: 10.1109/CISP-BMEI.2016.7852791.

[15] Wael Elloumi, Abdelhakim Latoui, Raphaël Canals, Aladine Chetouani, and Sylvie Treuillet. Indoor pedestrian localization with a smartphone: A comparison of inertial and vision-based methods. *IEEE Sensors Journal*, 16(13):5376–5388, 2016. doi: 10.1109/JSEN.2016.2565899.

[16] Plamen Levchev, Michael N. Krishnan, Chaoran Yu, Joseph Menke, and Avideh Zakhor. Simultaneous fingerprinting and mapping for multimodal image and wifi indoor positioning. In *2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, pages 442–450, 2014. doi: 10.1109/IPIN.2014.7275515.

[17] Damian Grzechca, Tomasz Wróbel, and Patryk Bielecki. Indoor location and idetification of objects with video survillance system and wifi module. In *2014 International Conference on Mathematics and Computers in Sciences and in Industry*, pages 171–174, 2014. doi: 10.1109/MCSI.2014.52.

[18] Yu-Yao Chen, Shih-Ping Huang, Ting-Wei Wu, Wei-Ting Tsai, Chong-Yi Liou, and Shau-Gang Mao. Uwb system for indoor positioning and tracking with arbitrary target orientation, optimal anchor location, and adaptive nlos mitigation. *IEEE Transactions on Vehicular Technology*, 69(9):9304–9314, 2020. doi: 10.1109/TVT.2020.2972578.

[19] Kabalan Chaccour and Georges Badr. Computer vision guidance system for indoor navigation of visually impaired people. In *2016 IEEE 8th International Conference on Intelligent Systems (IS)*, pages 449–454, 2016. doi: 10.1109/IS.2016.7737460.

[20] Esteban Bayro Kaiser and Michael Lawo. Wearable navigation system for the visually impaired and blind people. In *2012 IEEE/ACIS 11th International Conference on Computer and Information Science*, pages 230–233, 2012. doi: 10.1109/ICIS.2012.118.

[21] Bing Li, Juan Pablo Muñoz, Xuejian Rong, Qingtian Chen, Jizhong Xiao, Yingli Tian, Aries Arditi, and Mohammed Yousuf. Vision-based mobile indoor assistive navigation aid for blind people. *IEEE Transactions on Mobile Computing*, 18(3):702–714, 2019. doi: 10.1109/TMC.2018.2842751.

[22] Ruxandra Tapu, Bogdan Mocanu, and Titus Zaharia. Wearable assistive devices for visually impaired: A state of the art survey. *Pattern Recognition Letters*, 137:37–52, 2020. ISSN 0167-8655. doi: https://doi.org/10.1016/j.patrec.2018.10.031. URL `https://www.sciencedirect.com/science/article/pii/S0167865518308602`. Learning and Recognition for Assistive Computer Vision.

[23] Guojun Yang and Jafar Saniie. Sight-to-sound human-machine interface for guiding and navigating visually impaired people. *IEEE Access*, 8:185416–185428, 2020. doi: 10.1109/ACCESS.2020.3029426.

[24] Summan Zaib, Shah Khusro, Shaukat Ali, and Fakhre Alam. Smartphone based indoor navigation for blind persons using user profile and simplified building information model. In *2019 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, pages 1–6, 2019. doi: 10.1109/ICECCE47252.2019.8940799.

[25] Saleh Alghamdi, Ron van Schyndel, and Ahmed Alahmadi. Indoor navigational aid using active rfid and qr-code for sighted and blind people. In *2013 IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing*, pages 18–22, 2013. doi: 10.1109/ISSNIP.2013.6529756.

[26] Mats E. Nilsson and Bo N. Schenkman. Blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences. *Hearing Research*, 332:223–232, 2016. ISSN 0378-5955. doi: https://doi.org/10.1016/j.heares.2015.09.012. URL `https://www.sciencedirect.com/science/article/pii/S0378595515300174`.

[27] Lore Thaler, Stephen R Arnott, and Melvyn A Goodale. Neural correlates of natural human echolocation in early and late blind echolocation experts. *PLoS One*, 6(5):e20162, May 2011.

[28] Alexandre Alahi, Raphael Ortiz, and Pierre Vandergheynst. Freak: Fast retina keypoint. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pages 510–517, 06 2012. doi: 10.1109/CVPR.2012.6247715.

[29] D. Croce, L. Giarré, F.G. La Rosa, E. Montana, and I. Tinnirello. Enhancing tracking performance in a smartphone-based navigation system for visually impaired people. pages 1355–1360, 2016. doi: 10.1109/MED.2016.7535871.

[30] Alexandre Alahi, Raphael Ortiz, and Pierre Vandergheynst. Freak: Fast retina keypoint. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pages 510–517, 06 2012. doi: 10.1109/CVPR.2012.6247715.

[31] Andrew D Brown. *Temporal weighting of binaural cues for sound localization.* University of Washington, 2012.

[32] Reginald G Golledge, James R Marston, Jack M Loomis, and Roberta L Klatzky. Stated preferences for components of a personal guidance system for nonvisual navigation. *Journal of Visual Impairment & Blindness*, 98(3):135–147, 2004.