# TERRAIN AWARENESS MOBILITY MODEL TO SUPPORT OUTDOOR MOBILITY FOR PEOPLE WITH VISION IMPAIRMENT

**By**

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**Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

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**Chairman : Azrina binti Kamaruddin, PhD**
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Vision impairment is defined as any degree of impairment to a person's ability to see that affects his or her daily life. Changes in the ground surface (presence of terrain types) represent a significant challenge for people with vision impairment (PVI). While enormous research work proposed valuable solutions that improved PVI mobility, most of these studies investigated detecting obstacles above the ground and addressing navigation problems, with an insufficient investigation into terrain hazards. In addition to the lack of spatial information provided, which is mostly limited to vibration or audio signals. To address this gap, this study developed a Terrain Awareness Mobility Model (TAM2) to support outdoor mobility for PVI. TAM2 aims to improve terrain awareness by incorporating providing spatial information during mobility. The provided information improves instant mobility performance and facilitates the formation of the cognitive map of the environment, which can support safe and independent outdoor mobility. In this study, the User-Centred Design (UCD) approach was adopted, which involved engaging the target group throughout all research phases. The research design applied the exploratory mixed method, comprising qualitative research, then proposed the solution according to the findings, and finally, evaluated the solution quantitatively. To gather the users' requirements and expectations, a qualitative study was conducted with two groups of participants. The first group consisted of four experts whose job is to empower the life quality of PVI, while the second group comprised 15 participants with vision impairment. The study utilized three research instruments during this phase, a semi-structured interview, a mobility observation session in a familiar environment, and a mobility observation session in an unfamiliar environment. Thematic analysis was applied, and the findings outlined the primary components of TAM2. TAM2 contains three main components; user model, terrain detection model, and learning model. For the prototyping phase, the study employed the deep learning detection framework YOLOv4-tiny algorithm to implement a real-time terrain detection model. This detection model was integrated with an Android detection app to detect specific types of terrain. Additionally, the app was equipped with a speech message feedback function to convey spatial information, including terrain type, direction, and approximate distance.

Furthermore, a real-world quasi-experiment was conducted with 14 participants with vision impairment to evaluate TAM2 effectiveness through the app. The experiment measured the terrain type detection performance and feedback effectiveness, in addition to the usability of the app. Quantitative analysis via the Mann-Whitney U test technique with p-value = 0.05 was applied to assess the mobility performance improvement and cognitive map formation. The analysis revealed a statistically significant improvement in the users' mobility performance and cognitive map formation for the users who utilized the app. Additionally, the questionnaire descriptive analysis revealed that 71.4% of the participants agreed with the app's effectiveness and usability. This result indicates that TAM2 is able to support outdoor mobility for PVI. The terrain detection app can be used by the PVI community to improve their terrain awareness. As well the provided measurement methods can assist stakeholders in teaching locomotion for PVI. Moreover, TAM2 can serve as a roadmap for researchers investigating mobility for PVI, outlining the main requirements of the target group and how to achieve these requirements to progress the research. This could lead to the development of ATs that are better suited to PVI requirements (e.g., ATs that complement the white cane) and more usable that improve outdoor mobility for PVI. Accordingly, TAM2 and the terrain detection app represent the key contribution of this study.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**MODEL MOBILITI KESEDARAN TERAIN UNTUK MENYOKONG MOBILITI LUAR BAGI ORANG CACAT PENGLIHATAN**

Oleh

**MALKAWI ABEER DIRAR YOUSEF**

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Kecacatan penglihatan ditakrifkan sebagai sebarang tahap kecacatan kepada keupayaan penglihatan seseorang yang menjejaskan kehidupan sehariannya. Perubahan pada permukaan tanah (kewujudan jenis terain) merupakan cabaran yang signifikan bagi orang yang cacat penglihatan (PVI). Manakala kerja penyelidikan yang besar mengesyorkan penyelesaian yang berguna bagi memperbaiki mobiliti PVI, kebanyakan kajian tersebut menyelidiki pengesanan halangan di atas tanah dan menangani masalah navigasi, dengan penyelidikan yang tidak mencukupi mengenai bahaya terain. Selain kekurangan maklumat spatial yang disediakan, yang kebanyakannya terhad kepada getaran atau isyarat audio. Untuk mengatasi jurang tersebut, kajian ini membangunkan Model Mobiliti Kesedaran Terain (TAM2) bagi menyokong mobiliti luar untuk PVI. TAM2 bertujuan untuk memperbaiki kesedaran terain melalui penginkorporasian penyediaan maklumat ruangan ketika mobiliti. Maklumat yang diberi dapat meningkatkan prestasi mobiliti segera dan memudahkan pembentukan peta kognitif persekitaran, yang dapat menyokong mobiliti luar yang selamat dan independen. Dalam kajian ini, pendekatan Reka Bentuk Berpusatkan Pengguna (UCD) telah diterima pakai, yang melibatkan penglibatan kumpulan sasaran di sepanjang semua fasa penyelidikan. Reka bentuk penyelidikan mengaplikasi kaedah campuran eksploratori, terdiri daripada penyelidikan kualitatif, kemudian mengesyorkan penyelesaian bergantung kepada dapatan, dan akhirnya, menilai penyelesaian tersebut secara kuantitatif. Bagi mengumpul keperluan dan ekspektasi pengguna, kajian kualitatif telah dijalankan dengan dua kumpulan partisipan. Kumpulan pertama terdiri daripada empat pakar yang kerja mereka adalah untuk memperkasakan kualiti hidup PVI, manakala kumpulan kedua terdiri daripada 15 partisipan yang cacat penglihatan. Kajian ini menggunakan tiga instrumen penyelidikan ketika fasa ini, temu bual separa berstruktur, sesi pemerhatian mobiliti dalam persekitaran yang biasa, dan sesi pemerhatian mobiliti dalam persekitaran yang tidak biasa. Analisis tematik telah diaplikasikan, dan dapatan menggariskan komponen primer bagi TAM2. TAM2 mengandungi tiga komponen utama; model pengguna, model pengesanan terain, dan model pembelajaran. Bagi fasa pemprototaipan, kajian ini menggunakan rangka pengesanan pembelajaran mendalam

YOLOv4-algoritma kecil bagi mengimplentasi model pengesanan terain masa sebenar. Model pengesanan ini telah diintegrasikan dengan app pengesanan Android bagi mengesan jenis terain yang spesifik. Di samping itu, app tersebut telah dilengkapi dengan fungsi maklum balas mesej pertuturan bagi menyampaikan maklumat ruangan, termasuk jenis terain, tunjuk arah, anggaran jarak. Tambahan pula, eksperimen dunia sebenar telah dijalankan dengan 14 partisipan yang cacat penglihatan bagi menilai keberkesanan TAM2 melalui app tersebut. Percubaan mengukur prestasi pengesanan jenis rupa bumi dan keberkesanan maklum balas, di samping kebolehgunaan apl. Analisis Kuantitatif melalui teknik ujian Mann-Whitney U dengan nilai $p = 0.05$ telah diaplikasikan bagi menilai penambahbaikan prestasi mobiliti dan pembentukan peta kognitif. Analisis memperlihatkan penambahbaikan yang signifikan secara statistik dalam prestasi mobiliti pengguna dan pembentukan peta kognitif bagi pengguna yang memanfaatkan app tersebut. Selain itu, analisis deskriptif soal selidik mendedahkan bahawa 71.4% daripada peserta bersetuju dengan keberkesanan dan kebolehgunaan aplikasi. Dapatan kajian menunjukkan bahawa TAM2 berupaya untuk menyokong mobiliti luar bagi PVI. App pengesanan terain dapat digunakan oleh komuniti PVI bagi meningkatkan kesedaran mereka mengenai terain. Di samping itu kaedah penilaian yang disediakan dapat membantu pemegang taruh dalam pengajaran pergerakan bagi PVI. Lebih-lebih lagi, TAM2 dapat berfungsi sebagai peta hala tuju bagi penyelidik yang menyelidiki mobiliti bagi PVI, menggariskan keperluan utama kumpulan sasaran dan cara untuk mencapai keperluan tersebut bagi memajukan penyelidikan. Ini boleh membawa kepada pembangunan AT yang lebih sesuai dengan keperluan PVI (cth., AT yang melengkapkan tongkat putih) dan lebih boleh digunakan yang meningkatkan mobiliti luar untuk PVI. Sehubungan itu, TAM2 dan aplikasi pengesanan rupa bumi mewakili sumbangan utama kajian ini.

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In the name of ALLAH, the Most Gracious and the Most Merciful.

الحمد لله الذي بنعمته تتم الصالحات

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| | |
|---|---|
| ADL | Activities of Daily Living |
| API | Application Programming Interface |
| AR | Augmented Reality |
| AT | Assistive Technology |
| CBR | Community Base Rehabilitation instructor |
| CNN | Convolutional Neural Network |
| COCO | Common Objects In Context |
| CVI | Content Validity Index |
| EOA | Electronic Orientation Aid |
| ETA | Electronic Travel Aid |
| FCN | Fully Convolutional Network |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| GPU | Graphics Processing Unit |
| HCD | Human-Centered Design |
| ICT | Information Communication Technology |
| I-CVI | Item-Content Validity Index |
| IPSAD | Interactive and Portable Sidewalk Assistive Device |
| IR | Infrared |
| JKEUPM | Ethics Committee Research Involving Human Subjects |
| LiDAR | Light Detection and Ranging |
| MAB | Malaysian Associations for Blind |
| mAP | mean Average Precision |
| MLP | Multilayer Perceptron |
| NCBM | National Council for the Blind, Malaysia |

| | |
|---|---|
| O&M | Orientation and Mobility |
| OKU | Orang Kurang Upaya |
| PLD | Position Locator Device |
| PVI | People with Vision Impairment |
| R&D | Research and Development department |
| R-CNN | Region Convolutional Neural Network |
| ResNet | Residual Neural Network |
| RNN | Recurrent Neural Network |
| SA | Situation Awareness |
| S-CVI | Scale-Content Validity Index |
| SD | Standard Deviation |
| SIFT | Scale Invariant Feature Transform |
| SoV | Sound of Vision |
| TAM2 | Terrain Awareness Mobility Model |
| TAWS | Terrain Awareness and Warning System |
| TDA | Terrain Detection App |
| TDM | Terrain Detection Model |
| UA | Universal Agreement |
| UCD | User-Centred Design |
| VI | Vision Impairment |
| VR | Virtual Reality |
| WD | Wearable Device |
| WHO | World Health Organization |
| YOLO | You Only Look Once |

# CHAPTER 1

# INTRODUCTION

In the last two decades, significant research efforts have been directed toward facilitating outdoor mobility for people with vision impairment (PVI). These efforts have mainly focused on developing obstacle detection and wayfinding techniques, which have significantly advanced the field. However, limited attention has been given to addressing the critical issue of improving terrain awareness for PVI. To bridge this research gap, this study examines three key areas: outdoor mobility for PVI, terrain awareness mobility models, and computerized support. The integration of these domains offers a comprehensive solution to enhance terrain awareness for PVI. This introduction chapter comprises various sections that serve distinct purposes. Section 1.1 presents the motivation for conducting this study. Section 1.2 explains the problem statement. Section 1.3 puts forth the research questions that the study seeks to address. Section 1.4 outlines the research objectives that the study aims to achieve. Section 1.5 discusses the study scope. Section 1.6 explains the contributions that the study makes to the existing knowledge. Lastly, Section 1.7 presents the organization of the thesis, which provides a roadmap for the subsequent chapters.

## 1.1 Motivation

According to statistics provided by the World health organization (WHO), in 2022, there are approximately one billion individuals worldwide who are experiencing some degree of vision impairment, a significant proportion (80%) of which could potentially be treated, as stated by the (WHO, 2022). Consequently, it can be inferred that around 200 million PVI should adapt to this condition on a daily base, which can adversely impact their ability to carry out routine activities and increase their reliance on others for assistance, thereby posing a potential threat to their life.

Outdoor mobility in an unfamiliar environment is one of the severe challenges PVI faces daily. It is one of the primary factors that impact their quality of life economically and socially (Hersh & Johnson, 2008; Meza-de-Luna et al., 2019). Researchers have indicated that most PVI rely on accompanying a sighted person to visit an unfamiliar place (Pissaloux & Velázquez, 2017); Banovic et al. (2013). Consequently, improving mobility for PVI has drawn enormous attention in both academia and industry over the past two decades. Numerous assistive technologies have been developed to accomplish mobility challenges faced by PVI. However, the proposed systems primarily emphasized detecting and avoiding obstacles above the ground and solving navigation problems, as reported by (Bai et al., 2019; Bochsler et al., 2013).

In contrast, diverse terrain types constitute a tangible hazard with direct implications for the safety, independence, and proficient navigation of individuals with VI (Chai et al., 2018; Smith et al., 1992). These perils have the potential to exert a considerable influence on pivotal aspects such as employment prospects, overall health, and involvement in social activities within the specified demographic.

Despite the potential risk associated with terrain types, this study determined a lack in the literature regarding investigating and providing solutions for PVI to avoid terrain hazards and improve their terrain awareness.

Moreover, the revolution of deep learning techniques and their effective detection performance in real-time inspired researchers to employ this technology to assist PVI in reducing the influence of disability on daily life.

Therefore, the primary motivation of this research work is to employ information technology to propose a solution that aims to improve PVI's terrain awareness and support their safe and independent outdoor mobility, which could reduce the former challenges and enhance their quality of life.

## 1.2 Problem Statement

The first problem found in the literature body is that changes in the ground surface (presence of terrain type) represent a significant risk factor that impacts the physical safety of PVI. According to Walter (Walter et al., 2013), the level of changes on a flat surface for a 4 cm step or 3 cm slope is considered a critical hazard for PVI, as cited by (Cloix et al., 2016). The challenges of terrain types for PVI are compounded by the limitation of the most popular conventional traveling aid (i.e., white cane) to detect these types in several situations. This limitation stems from the movement and tipping way of the cane during navigation, as well as the terrain type size (Hersh & Johnson, 2008; Pissaloux & Velázquez, 2017). Smith's research identified terrain hazards as one of the top five mobility problems PVI faces daily (Smith et al., 1992). Furthermore, most warning signs for terrain types are typically visual in nature, whereas the urban environment has been designed primarily for sighted individuals (Johnston, 2013).

Many studies have proposed both theoretical and practical solutions that support mobility for PVI to a large extent. However, the majority of these research works focused on detecting and avoiding obstacles above the ground while avoiding addressing potential ground hazards, such as stairs and holes (Bai et al., 2019; Chai et al., 2018). Despite the significant challenges the PVI community struggles with regarding terrain hazards, insufficient research was conducted to identify the factors that impact PVIs' mobility due to terrain types and propose solutions that improve terrain awareness. Some research works involve terrain types within their scope, but their primary aim has been detecting obstacles, with only limited types of terrain included within these obstacles. For instance, the research involved detecting stairs (Kunta et al. 2020; Sun et al. 2019; Bashiri et al. 2018) and included potholes (Ahmed et al. 2018; Khan Kundu et al. 2018), where these studies are limited in scope to address terrain types.

On the other hand, this research endeavors to provide a conceptual and practical solution that bridges the existing gap in improving terrain awareness to support safe outdoor mobility for PVI. This research strives to address the terrain challenges based on PVI requirements, as perceived by experts who work to empower PVI life quality and participants from the PVI community.

The second problem in the mobility for the PVI domain is the limited safety spatial information provided to the PVI. Providing PVI with sufficient information during navigation can improve their mobility performance to protect their safety (Pearson et al., 2015). However, several researchers highlighted that the majority of existing solutions for PVI provide low-level information, which falls short of meeting the spatial information that PVI requires for safe mobility in terms of obstacle detection and environmental awareness (Chen et al. 2021; Pissaloux et al., 2017; Banovic et al., 2013).

Massive research studies have proposed systems that convey feedback in the form of haptic (Chai et al., 2018) or acoustic warning (Tachiquin et al., 2021; K. Yang, Wang, et al., 2018) to assist the individual in navigation. However, such feedback mechanisms are unreliable in providing even the minimum required spatial information unless it is to warn of an imminent hazard. A diverse range of spatial information is necessary to improve the user's terrain awareness, which generates a clear comprehension and perception of the environmental structure (K. Yang, Wang, et al., 2018; R. Yang et al., 2011). Meanwhile, spatial knowledge theories consider understanding the environment structure induced by the user's perception and then followed by reaction (Pissaloux & Velázquez, 2017; Spiers, 2016).

El-Taher's research argued that the speech message constitutes the most widely used feedback mechanism in recent studies (El-Taher et al., 2021). In contrast, the provided information has been mostly limited to navigation guidance, such as instructions to turn left or move right in the Van Der study (Van Der Bie et al., 2019) or obstacle presence warning (e.g., "stop, obstacle detected") (Sim et al., 2019), and identifying the obstacle's name without providing the necessary details such as direction, for instance, "stairs" (Chandra et al., 2020; Yang, Wang, et al., 2018).

However, this study proposed a speech message feedback mechanism to convey more comprehensive and direct information, considering avoiding the potential for overwhelming data (Hersh & Johnson, 2008). The delivered information includes the terrain type, direction (up or down), and the estimated distance to reach it. Such information can significantly stimulate the users' awareness of the terrain type in front of them. Hence, they recognize the presence of a nearby hazard that causes them to navigate carefully to find this terrain type, then verify and tackle it safely and effectively. Providing individuals with sufficient information assists them in understanding the surrounding environment and can play a pivotal role in improving their terrain awareness (Rachburee & Punlumjeak, 2021; K. Yang, Bergasa, et al., 2018)

The third problem we found in the literature pertains to the lack of providing PVI with adequate perception of various types of terrain in the surrounding environment, which can facilitate the formation of the cognitive map. This is due to the limited scope of previous studies according to the tackled number of terrain types, where many studies addressed either a single type of terrain (Tan et al., 2019; Sun et al., 2019) or only two types of terrain (Kunta et al., 2020; Yang Bergasa et al., 2018; Chai et al., 2018). Consequently, while such studies may provide individuals with instant mobility assistance, they offer limited spatial knowledge of the surrounding environment.

Researchers agreed that cognitive map formation required imagery of environmental elements and spatial relations among these elements, such as distance, directions, and scales (Kitchin, 2015; Kitchin & Blades, 2002). Therefore, collecting spatial information about more elements enables individuals to generate more spatial relations and a robust perception of the environment. Hersh has highlighted the limitation of many travel aids by the lack of providing PVI with a spatial comprehension of the environment (Hersh, 2016). Furthermore, Banovic has pointed out that most research works provide users with information for immediate requirements, disregarding the need for information that can aid in cognitive map formation (Banovic et al., 2013).

This study investigated four terrain types, including potholes, drains, ascending stairs, and descending stairs. These structures can function as cues and landmarks that PVI can memorize and use to establish relationships among them from one side and with the environment from another side. These relations facilitate individuals' ability to generate the cognitive map, as Quiñones mentioned based on Lynch's findings in 1960 (Quiñones et al., 2011).

The current study aims to offer PVI sufficient information about the terrain type they are approaching during navigation. This information prompts individuals to search for the mentioned terrain type and directly contact it to collect additional necessary information, such as depth or height, to tackle the situation safely. This process enables PVI to engage in spatial learning using both resources-based and navigation-based strategies simultaneously. We hypothesize that this approach will improve the formation of the cognitive map, improve terrain awareness, and ultimately support outdoor mobility for PVI.

As a result, the existing research regarding terrain awareness for the PVI field is inadequate to provide effective outdoor mobility for the target group. Therefore, there is a necessity to develop a terrain mobility model that can overcome this gap and support outdoor mobility for the PVI community. Figure 1.1 illustrates the interrelated points of the problem statement.

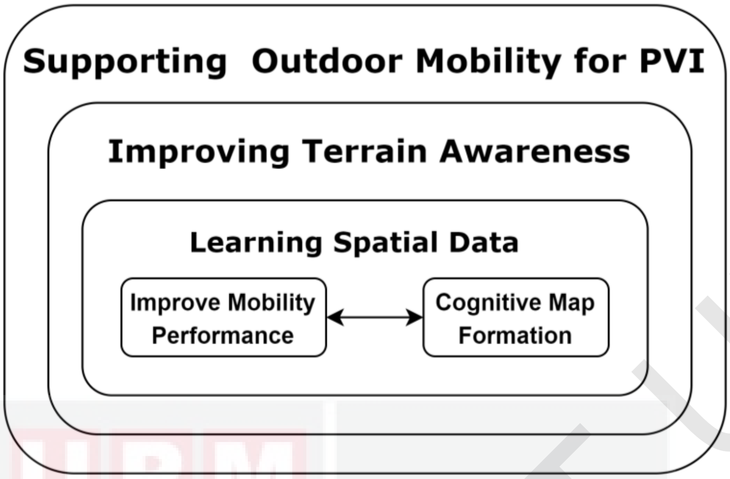


**Figure 1.1 : Problem Statement Points**

## 1.3 Research Questions

This study aims to answer the following research questions.

RQ 1- What factors impact the mobility of PVI regarding the presence of terrain types?

a. How do terrain types impact the safety of PVI?

b. Which specific types of terrain pose the greatest danger for PVI?

RQ 2- What are the parameters of the mobility assistant model that improve terrain awareness and support safe outdoor mobility for PVI?

RQ 3- How can the prototype solution be proposed to improve terrain awareness of PVI?

a. What design features are most effective?

b. Which feedback mechanism, haptic or auditory, is most appropriate?

c. What spatial information is necessary for good performance?

RQ 4- To what extent does the proposed model contribute to improving terrain awareness and supporting safe mobility for PVI?

a. How can the model improve mobility performance?

b. How can the model improve cognitive map formation?

c. What is the prototype's effectiveness and usability level from the users' point of view?

## 1.4 Research Objectives

This study aims to support outdoor mobility for PVI by improving their terrain awareness. This aim can be achieved by identifying and evaluating a terrain awareness mobility model.

Objective 1- To identify the factors that impact PVI mobility due to the presence of various terrain types. The factors include behaviors, challenges, requirements, and features of the solution, which is able to improve PVI terrain awareness.

This objective focuses on the terrain types and the factors that make them significant challenges that impact mobility for PVI. These factors include the behaviors of PVI to tackle terrain types, the main terrain types that form the significant problems, and the requirements and solutions that can improve terrain awareness. In contrast, many research works investigated mobility for PVI and discarded the terrain challenges.

Objective 2- To propose a mobility model that provides sufficient safety spatial information and enables individuals to visualize the environment regarding the terrain types, which improves terrain awareness and supports outdoor mobility for PVI.

Achieving the first objective should provide us with the essential features of the solution that can address terrain challenges. Consequently, objective 2 deciphers the properties of the solution into a theoretical model that resolves the issues found, for example, the delivered spatial information and the appropriate feedback mechanism.

Objective 3- To design and implement a terrain awareness mobility model prototype.

The prototype should implement the theoretical features of the model achieved in objective two into a practical mobile application. Researchers agreed that collecting spatial information about more elements enables individuals to visualize the environment, generate more spatial relations, and facilitate cognitive map formation (Kitchin & Blades, 2002; Pissaloux, Velazquez, Hersh, et al., 2017). This app should use an effective real-time detection algorithm to detect four types of terrain in front of the user and convey their names, directions (i.e., up or down), and distance to reach within five meters as speech message feedback. Thus, the app will provide sufficient spatial information about various terrain types, which enables the user to visualize the area by linking these terrain types together and with the other environmental elements.

Objective 4- To evaluate the effectiveness of the proposed terrain awareness mobility model via testing the prototype.

An experimental study with participants with VI should be conducted to evaluate the proposed model. The experiment will evaluate the improvement of the terrain awareness of the users via testing the improvement of mobility performance and facilitating cognitive map formation. Moreover, a questionnaire will be used to test the effectiveness and usability of the app from the users' perspective.

## 1.5 Research Scope

Alterations in the ground surface, precisely the existence of diverse terrain types, constitute a tangible risk that impacts PVI's physical safety, independence, and effective navigation. These threats may influence the target group's employment opportunities, health and well-being, and social involvement.

Furthermore, the revolution of deep learning methodologies and their demonstrated efficacy in real-time detection has inspired researchers to leverage this technology for aiding individuals with VI, mitigating the impact of disability on their daily activities.

TAM2 was developed to improve the terrain awareness for PVI. It was designed for adult individuals with vision impairment at levels B1 and B2. It covers outdoor mobility in terms of the challenges associated with four types of terrain found in the pedestrian zone. The investigated terrain types include potholes, drains, and ascending and descending stairs.

The recruitment of participants for the data gathering phase was carried out in collaboration with the Malaysian Associations for Blind (MAB) in KL and Ipoh. The participants who evaluated the prototype belong to the MAB-KL. The sample size is considered small compared to other studies involving participants without disabilities, where this size is sufficient for people with disabilities. To guarantee the safety of the participants, the observation and evaluation sessions were conducted in controlled areas with low traffic and pedestrians.

## 1.6 Research Contributions

This study contributes to the knowledge of the following aspects,

The first contribution is the Terrain Awareness Mobility Model (TAM2). This computer-based model improves the terrain awareness of PVI. It explains individuals' navigation behaviors when particular types of terrain are present and before the individual physically contacts it. The TAM2 clarifies the process of interaction with that terrain and tackling it. Finally, TAM2 portrays individuals learning from that experience and improving the cognitive map of that environment. Details in Chapter 5.

The second contribution is a complication of PVI mobility behaviors and requirements. This list is based on the findings of the studies conducted with experts and participants from the PVI community. Government organizations and researchers can utilize these requirements to conduct further research aimed at improving mobility for PVI. Details in Chapter 4.

The third contribution of this study is the Terrain Detection Model (TDM). This model deployed deep learning techniques using the YOLOv4 algorithm. TDM trained the image dataset for the four investigated types of terrain, which involved potholes, drains, ascending stairs, and descending stairs. The model's detection accuracy, as measured by mean average precision (mAP), is 99.11, and the inference time ranges from 160 to 250 milliseconds. Details in Chapter 6.

The fourth contribution is the Terrain Detection App (TDA). Even though this App is adapted from an existing Android detection App available on GitHub (Shakeel, 2020), significant modifications were implemented to enhance its functionality. The study integrated the TDM into the Android App. Then, to achieve the study objective, new functions were programmed from scratch. For instance, the distance calculation, preparing feedback and conveying feedback functions. The app can be utilized by PVI to improve their terrain awareness. Details in Chapter 6.

The fifth contribution of this research is the terrain images dataset, which comprises 3,189 images. The dataset includes 796 pothole images, 787 drain images, 803 ascending stairs, and 803 descending stairs. This dataset was collected from two sources, including 1,780 images from open-source websites like Google and Bing. In contrast, 1,409 images were self-captured from seven different locations in the UPM campus and its surrounding areas. Details in Chapter 6.

The sixth contribution of this research is the empirical evaluation of the effectiveness of the proposed terrain awareness mobility model in improving mobility performance and facilitating cognitive map formation. The evaluation results are also presented. The evaluation process applied in this study, based on the mobility behavioral activities related to mobility performance, is a novel contribution to the existing knowledge. Details in Chapter 7.

The seventh contribution to this study involves a map drawing technique using a magnetic whiteboard and magnetic figures representing landmarks. Although magnetic figures and whiteboards have been utilized previously, they used animal shapes to indicate animal sounds that direct individuals to a particular location. In contrast, the figures we used in this study represent real environmental landmarks with representative shapes and sizes. Therefore, the experts from the National Council for the Blind, Malaysia (NCBM) and MAB have recommended using this map drawing technique to teach blind children about spatial information. Details in Chapter 7.

The last contribution to this study is the questionnaire aimed at assessing the effectiveness of the TDA. This questionnaire underwent validation through seven experts with relevant knowledge in the HCI field and working experience with PVI. The questionnaire achieved an acceptable context validity index and demonstrated adequate internal reliability. The questionnaire results provided evidence supporting the effectiveness of TAM2 in improving the terrain awareness of PVI. Details in Chapter 7.

## 1.7 Thesis Organization

This thesis comprises eight chapters.

Chapter 2 Literature Review. The chapter begins by outlining the background of people with vision impairment and outdoor mobility for PVI. It then proceeds to identify the concepts of spatial learning and terrain awareness. The chapter delves into the literature on mobility models for PVI and reviews the latest research developments in this domain.

Chapter 3 Methodology. The chapter outlines the research methodology we applied in this study. It describes the mixed-method design employed, including the qualitative method conducted to gather data and the quantitative techniques utilized to evaluate the proposed solution. The chapter explains the various research phases, starting from the literature review, studies with experts and participants with VI, the terrain awareness mobility model (TAM2) development, prototyping, and the evaluation phase.

Chapter 4 Experts and People with Vision Impairment Studies. This chapter discusses the instruments, analysis, and results of the data collection studies conducted with experts and PVI. The chapter elaborates on the employment of the instruments, which facilitated the collection of data on the outdoor mobility challenges facing PVI, particularly regarding terrain awareness. In addition to the target group's requirements and expectations to overcome these challenges.

Chapter 5 Terrain Awareness Mobility Model (TAM2). This chapter introduces the proposed TAM2 model as the primary contribution of this study. The chapter explains the three components of TAM2: the User Model, the Terrain Detection Model (TDM), and the Learning Model. This chapter elaborated on each of these components and their corresponding sub-components.

Chapter 6 TAM2 Prototyping. This chapter details the implementation process of TAM2. The implementation is divided into three main phases. Firstly, it involves developing the TDM by employing deep learning techniques using a convolutional neural network via the YOLOv4 algorithm. Secondly, it involves the development of an Android Terrain Detection App (TDA). Finally, the TDM was combined with the TDA, tested, and debugged the system.

Chapter 7 Results and Discussion. This chapter highlights the evaluation experiment of the TAM2 effectiveness through the prototype app. The chapter describes the participants, sites, and experiment procedure involved in the evaluation process. The chapter then presents the quantitative results of the study, which demonstrate the effectiveness of TAM2 in improving the terrain awareness of PVI. The results revealed the improvement in mobility performance and cognitive map formation, in addition to the effectiveness and usability of the TDA.

Chapter 8 Conclusion and Future Works. This chapter marks the close of this research study. The chapter revisits the research objectives and outlines the research limitations. The chapter also provides recommendations for future works based on the findings and limitations.

# REFERENCES

Abras, C., Maloney-Krichmar, D., & Preece, J. (2004). User Centered Design. In *Human-Computer Interaction*. SAGE. https://www.interaction-design.org/literature/topics/user-centered-design

Abuseta, Y., & Swesi, K. (2015). Design Patterns for Self Adaptive Systems Engineering. *International Journal of Software Engineering & Applications*, *6*(4), 11–28. https://doi.org/10.5121/ijsea.2015.6402

Achirei, S. D., Opariuc, I. A., Zvoristeanu, O., Caraiman, S., & Manta, V. I. (2021). Pothole Detection for Visually Impaired Assistance. *Proceedings - 2021 IEEE 17th International Conference on Intelligent Computer Communication and Processing, ICCP 2021*, 409–415. https://doi.org/10.1109/ICCP53602.2021.9733610

Afonso-Jaco, A., & Katz, B. F. G. (2022). Spatial Knowledge via Auditory Information for Blind Individuals: Spatial Cognition Studies and the Use of Audio-VR. *Sensors*, *22*, 4794. https://doi.org/10.3390/s22134794

Ahlmark, D. I. (2016). Haptic Navigation aids for the visually impaired. In *PhD Thesis-Lulea University of Technology- Sweden*. https://doi.org/10.1007/978-4-431-55772-2_14

Ahmed, F., Mahmud, S., & Yeasin, M. (2018). An Interactive Device for Ambient Awareness on Sidewalk for Visually Impaired. *2018 IEEE International Smart Cities Conference (ISC2)*, 1–6.

Albouys-Perrois, J., Laviole, J., Briant, C., & Brock, A. M. (2018). Towards a multisensory augmented reality map for blind and low vision people: A participatory design approach. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3173574.3174203

Alkhanifer, A. (2015). The Role of Situation Awareness Metrics in the Assessment of Indoor Orientation Assistive Technologies that Aid Blind Individuals in Unfamiliar Indoor Environments [Rochester Institute of Technology Rochester]. In *Theses* (Issue October). http://scholarworks.rit.edu/theses/8876

Alkhanifer, A., & Ludi, S. (2015). Disorientation factors that affect the situation awareness of the visually impaired individuals in unfamiliar indoor environments. *Universal Access in Human-Computer Interaction (UAHCI)*, *9178*, 89–100. https://doi.org/10.1007/978-3-319-20687-5_9

Ambrose, G., & Harris, P. (2010). Design Thinking. In *AVA Publishing SA*. AVA Publishing SA. https://books.google.com/books?id=9klpFfZDnWgC&pgis=1

*Awareness*. (n.d.). Alleydog.Com. Retrieved September 13, 2019, from https://www.alleydog.com/glossary/definition.php?term=Awareness

Babbie, E. (1990). *Survey Research Methods* (2nd ed.). Wadsworth Publishing. http://digilib.fisipol.ugm.ac.id/handle/15717717/11236

Baek, E., Cagiltay, K., & Frick, T. (2008). User-Centered Design and Development. In *Handbook of Research on Educational Communications and Technology* (pp. 659–670). Routledge.

Bai, J., Liu, Z., Lin, Y., Li, Y., Lian, S., & Liu, D. (2019). Wearable Travel Aid for Environment Perception and Navigation of Visually Impaired People. *Electronics*, *8*(6), 697. https://doi.org/10.3390/electronics8060697

Bala, M. M., & Vasundhara, D. N. (2023). Design, development and performance analysis of cognitive assisting aid with multi sensor fused navigation for visually impaired people. *Journal of Big Data*, *10*. https://doi.org/10.21203/rs.3.rs-1579158/v1

Banovic, N., Franz, R. L., Truong, K. N., Mankoff, J., & Dey, A. K. (2013). Uncovering information needs for independent spatial learning for users who are visually impaired. *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, 1–8. https://doi.org/10.1145/2513383.2513445

Barontini, F., Catalano, M. G., Pallottino, L., Leporini, B., & Bianchi, M. (2021). Integrating Wearable Haptics and Obstacle Avoidance for the Visually Impaired in Indoor Navigation: A User-Centered Approach. *IEEE Transactions on Haptics*, *14*(1), 109–122. https://doi.org/10.1109/TOH.2020.2996748

Bashiri, F., LaRose, E., Badger, J., Roshan, D., Yu, Z., & Peissig, P. (2018). *Object Detection to Assist Visually Impaired People: A Deep Neural Network Adventure*. 500–510. https://doi.org/10.1007/978-3-030-03801-4

*Behave*. (n.d.). Merriam Webster. Retrieved February 7, 2023, from https://www.merriam-webster.com/dictionary/behave

Benyon, D. (2014). Designing interactive systems, A comprehensive guide to HCI, UX and interaction design. In *PEARSON* (3rd ed.). PEARSON.

Bharambe, S., Thakker, R., Patil, H., & Bhurchandi, K. M. (2013). Substitute eyes for blind with navigator using android. *Proceedings - 2013 Texas Instruments India Educators' Conference, TIIEC 2013*, 38–43. https://doi.org/10.1109/TIIEC.2013.14

Bhatlawande, S., Deshpande, A., Deshpande, S., & Shilaskar, S. (2022). Proactive Detection of Pothole and Walkable Path for Safe Mobility of Visually Challenged. *2022 3rd International Conference for Emerging Technology, INCET 2022*, 1–5. https://doi.org/10.1109/INCET54531.2022.9824637

Bhole, S., & Dhok, A. (2020). Deep Learning based Object Detection and Recognition Framework for the Visually-Impaired. *Proceedings of the 4th International Conference on Computing Methodologies and Communication*, *ICCMC 2020*, *Iccmc*, 725–728. https://doi.org/10.1109/ICCMC48092.2020.ICCMC-000135

Bhongade, P., Girhay, S., Sheikh, A. M., Ghata, R., Ambadkar, S., & Dusane, C. (2022). Internet of Things - Enabled Smart Shoes for Blind People. *2022 IEEE Delhi Section Conference, DELCON 2022*. https://doi.org/10.1109/DELCON54057.2022.9753526

Bhowmick, & Hazarika. (2017). An insight into assistive technology for the visually impaired and blind people: state-of-the-art and future trends. *Journal on Multimodal User Interfaces*, *11*(2), 149–172. https://doi.org/10.1007/s12193-016-0235-6

Bigelow, A. E. (1996). Blind and Sighted Children's Spatial Knowledge of Their Home Environments. *International Journal of Behavioral Development*, *19*(4), 797–816. https://doi.org/10.1080/016502596385587

Bochkovskiy, A., Wang, C.-Y., & Liao, H.-Y. M. (2020). YOLOv4: Optimal Speed and Accuracy of Object Detection. *ArXiv:2004.10934*, *1*. https://doi.org/https://arxiv.org/abs/2004.10934

Bochsler, T. M., Legge, G. E., Gage, R., & Kallie, C. S. (2013). Recognition of ramps and steps by people with low vision. *Investigative Ophthalmology and Visual Science*, *54*(1), 288–294. https://doi.org/10.1167/iovs.12-10461

Bohus, D., & Horvitz, E. (2010). Facilitating multiparty dialog with gaze, gesture, and speech. *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction, ICMI-MLMI 2010, September*, 1–8. https://doi.org/10.1145/1891903.1891910

Bonnen, K., Matthis, J. S., Gibaldi, A., Banks, M. S., Levi, D. M., & Hayhoe, M. (2021). Binocular vision and the control of foot placement during walking in natural terrain. *Scientific Reports - Nature.Com*, *0123456789*, 1–12.

Boone, H. N., & Boone, D. A. (2012). Analyzing Likert Data. *Journal of Extension*, *50*(2), 1456–1466. https://doi.org/10.1007/s11172-017-1908-3

Brambring, M. (1985). MOBILITY AND ORIENTATION PROCESSES OF THE BLIND. *Warren DH, Strelow ER (Eds) Electronic Spatial Sensing for the Blind*, *99*, 493–508.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brayda, L., Leo, F., Baccelliere, C., Vigini, C., & Cocchi, E. (2019). A refreshable tactile display effectively supports cognitive mapping followed by orientation and mobility tasks: A comparative multi-modal study involving blind and low-vision participants. *MAHCI 2019 - Proceedings of the 2nd Workshop on Multimedia for Accessible Human Computer Interfaces, Co-Located with MM 2019, October*, 9–15. https://doi.org/10.1145/3347319.3356840

Breve, F., & Fischer, C. N. (2020). Visually Impaired Aid using Convolutional Neural Networks, Transfer Learning, and Particle Competition and Cooperation. *Proceedings of the International Joint Conference on Neural Networks*. https://doi.org/10.1109/IJCNN48605.2020.9207606

Brownlee, J. (2019). Deep Learning for Computer Vision Image Classification , Object Detection , and Face Recognition in Python UNLOCK Computer Vision With Deep Learning. *Deep Learning for Computer Vision*, 1–21. https://machinelearningmastery.com/deep-learning-for-computer-vision/

Brulé, E. (2020). *Thematic analysis in HCI*. UsabilityGeek. https://medium.com/usabilitygeek/thematic-analysis-in-hci-57edae583ca9

Caine, K. (2016). Local standards for sample size at CHI. *Conference on Human Factors in Computing Systems - Proceedings*, 981–992. https://doi.org/10.1145/2858036.2858498

Calder, D. J. (2010). Ecological solutions for the blind. *4th IEEE International Conference on Digital Ecosystems and Technologies - Conference Proceedings of IEEE-DEST 2010, DEST 2010*, 625–630. https://doi.org/10.1109/DEST.2010.5610585

*Cambridge Dictionary*. (n.d.). Cambridge. Retrieved November 21, 2020, from https://dictionary.cambridge.org/dictionary/english/expert

Caraiman, Morar, Owczarek, Burlacu, A., Rzeszotarski, D., Botezatu, N., Herghelegiu, P., Moldoveanu, F., Strumillo, P., & Moldoveanu, A. (2018). Computer Vision for the Visually Impaired: The Sound of Vision System. *Proceedings - 2017 IEEE International Conference on Computer Vision Workshops, ICCVW 2017*, *2018-Janua*, 1480–1489. https://doi.org/10.1109/ICCVW.2017.175

Carbon, C.-C. (2013). BiDimRegression : Bidimensional Regression Modeling Using R . *Journal of Statistical Software*, *52*(Code Snippet 1), 1–11. https://doi.org/10.18637/jss.v052.c01

Chai, A., Chun, B., Theng, L. B., Deverell, L., Mahmud, A. A. L., & Mccarthy, C. (2018). An Autonomous LiDAR Based Ground Plane Hazards Detector for the Visually Impaired. *IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES)*, 346–351.

Chai, A., & Lau, B. (2020). Exploring the outdoor performance of a lidar-based ground plane checking system for the visually impaired. *EAI Endorsed Transactions on Pervasive Health and Technology*, *6*(23), 1–8. https://doi.org/10.4108/eai.13-7-2018.165498

Chanana, P., Paul, R., Balakrishnan, M., & Rao, P. (2017). Assistive technology solutions for aiding travel of pedestrians with visual impairment. *Journal of Rehabilitation and Assistive Technologies Engineering*, *4*, 1–16. https://doi.org/10.1177/2055668317725993

Chandna, S., & Singhal, A. (2022). Towards Outdoor Navigation System for Visually Impaired People using YOLOv5. *Proceedings of the Confluence 2022 - 12th International Conference on Cloud Computing, Data Science and Engineering*, 617–622. https://doi.org/10.1109/Confluence52989.2022.9734204

Chandra, R., Yadav, S., Dutta, M., & Travieso-Gonzalez, C. (2020). Effective Multi-Object Detection and Smart Navigation Using Artificial Intelligence for Visually Impaired People. *Entropy*, *22*(9), 941. https://doi.org/doi:10.3390/e22090941

Chang, W. J., Su, J. P., Chen, L. B., Chen, M. C., Hsu, C. H., Yang, C. H., Sie, C. Y., & Chuang, C. H. (2020). An AI edge computing based W earable assistive device for visually impaired people zebra-crossing walking. *Digest of Technical Papers - IEEE International Conference on Consumer Electronics*, *2020-Janua*, 4–5. https://doi.org/10.1109/ICCE46568.2020.9043132

Chen, Z., Liu, X., Kojima, M., Huang, Q., & Arai, T. (2021). A wearable navigation device for visually impaired people based on the real-time semantic visual slam system. *Sensors*, *21*(4), 1–14. https://doi.org/10.3390/s21041536

Cheng, R., Wang, K., Yang, K., Long, N., Bai, J., & Liu, D. (2018). Real-time pedestrian crossing lights detection algorithm for the visually impaired. *Multimedia Tools and Applications*, *77*(16), 20651–20671. https://doi.org/10.1007/s11042-017-5472-5

Choi, D. S., Yang, T. H., Bang, W. C., & Kim, S. Y. (2018). Design of a Multi-Functional Module for Visually Impaired Persons. *International Journal of Precision Engineering and Manufacturing*, *19*(11), 1745–1751. https://doi.org/10.1007/s12541-018-0202-0

Cloix, S., Bologna, G., Weiss, V., Pun, T., & Hasler, D. (2016). Low-power depth-based descending stair detection for smart assistive devices. *Eurasip Journal on Image and Video Processing*, *33*(1). https://doi.org/10.1186/s13640-016-0133-6

Creswell, J., & Creswell, J. D. (2018). *Research Design Qualitative, Quantitative, and Mixed Methods Approaches* (5th Ed.). SAGE.

Cuturi, L. F., Aggius-Vella, E., Campus, C., Parmiggiani, A., & Gori, M. (2016). From science to technology: Orientation and mobility in blind children and adults. *Neuroscience and Biobehavioral Reviews*, *71*, 240–251. https://doi.org/10.1016/j.neubiorev.2016.08.019

da Mota Moura, A. M., de Oliveira, R. F., Fernandes, E., de Lacerda Caetano, L., Manoel, L., & do Prado Leite, J. C. S. (2019). Improving urban mobility for the visually impaired using the awareness quality. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3364641.3364649

Darin, T., Andrade, R., & Sánchez, J. (2022). Usability evaluation of multimodal interactive virtual environments for learners who are blind: An empirical investigation. *International Journal of Human Computer Studies*, *158*(December 2020). https://doi.org/10.1016/j.ijhcs.2021.102732

Davis, L. L. (1992). Instrument review: Getting the most from a panel of experts. *Applied Nursing Research*, *5*(4), 194–197. https://doi.org/10.1016/S0897-1897(05)80008-4

Davison, A. J., Reid, I. D., Molton, N. D., & Stasse, O. (2007). MonoSLAM: Real-time single camera SLAM. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *29*(6), 1052–1067. https://doi.org/10.1109/TPAMI.2007.1049

De Padua A. Oliveira, A., & Cysneiros, L. M. (2006). Defining strategic dependency situations in requirements elicitation. *WER 2006 - 9th Workshop on Requirements Engineering*, 12–23.

Del Greco, L., Walop, W., & McCarthy, R. H. (1987). Questionnaire development: 2. Validity and reliability. *Canadian Medical Association Journal*, *136*(7), 699–700.

Dhemba Ishmael. (2015). The Use of Auditory, Tactual, Olfactory and Kinaesthetic Senses\nIn Developing Orientation and Mobility (O & M) Skills to Learners with Congenital Blindness (CB)\n. *IOSR Journal Of Humanities And Social Science (IOSR-JHSS)*, *20*(2), 34–44. https://doi.org/10.9790/0837-20213444

Dimas, G., Diamantis, D. E., Kalozoumis, P., & Iakovidis, D. K. (2020). Uncertainty-aware visual perception system for outdoor navigation of the visually challenged. *Sensors (Switzerland)*, *20*(8). https://doi.org/10.3390/s20082385

Disabled World. (n.d.). *Is Visually Impaired the Same as Being Legally Blind*. Disabled World. Retrieved November 10, 2018, from https://www.disabled-world.com/disability/types/vision/visually-impaired-blind.php%0D

Dix, A., Finlay, J., Abowd, G., & Beale, R. (2004). Human–Computer Interaction. In *Systems, Controls, Embedded Systems, Energy, and Machines* (3rd ed.). Prentice Hall.

Dodds, A. G., Carter, D. D. C., & Howarth, C. I. (1983). Improving objective measures of mobility. *Journal of Visual Impairment and Blindness*, *77*(9), 438–442. https://doi.org/10.1177/0145482x8307700904

Downs, R. M., & Stea, D. (2011). Cognitive maps and spatial behavior: Process and products. In *Image and Environment: Cognitive Mapping and Spatial Behavior* (pp. 8–26). John Wiley & Sons.

Dumas, J., & Fox, J. (2007). Usability Testing: Current Practice and Future Directions. In *The Human-Computer Interaction Handbook* (2nd ed., p. 22). Taylor & Francis.

Education. (2013). *Difference between Model and framewok*. https://www.differencebetween.com/difference-between-model-and-vs-framework/

El-Taher, F. E. Z., Taha, A., Courtney, J., & McKeever, S. (2021). A systematic review of urban navigation systems for visually impaired people. *Sensors*, *21*(9), 1–35. https://doi.org/10.3390/s21093103

Elmannai, W. M., & Elleithy, K. M. (2018). A Highly Accurate and Reliable Data Fusion Framework for Guiding the Visually Impaired. *IEEE Access*, *6*, 33029–33054. https://doi.org/10.1109/ACCESS.2018.2817164

Endsley, M. R. (1988). Design and Evaluation for Situation Awareness Enhancement. *Proceedings of the Human Factors Society Annual Meeting*, *32*(2), 97–101. https://doi.org/10.1177/154193128803200221

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32–64. https://doi.org/10.1518/001872095779049543

Endsley, M. R. (2016). Designing for Situation Awareness: An Approach to User-Centered Design. In 2nd (Ed.), *Taylor & Francis*. Taylor & Francis. https://doi.org/10.1201/b11371

Fang, J., Liu, Q., & Li, J. (2021). A Deployment Scheme of YOLOv5 with Inference Optimizations Based on the Triton Inference Server. *2021 IEEE 6th International Conference on Cloud Computing and Big Data Analytics, ICCCBDA 2021*, 441–445. https://doi.org/10.1109/ICCCBDA51879.2021.9442557

*Flutter*. (n.d.). Google. Retrieved November 28, 2020, from https://flutter.dev/

Fourtassi, M., Hajjioui, A., Urquizar, C., Rossetti, Y., Rode, G., & Pisella, L. (2013). Iterative Fragmentation of Cognitive Maps in a Visual Imagery Task. *PLoS ONE*, *8*(7), 1–8. https://doi.org/10.1371/journal.pone.0068560

Freundschuh, S., & Kitchin, R. (2000). Cognitive mapping: Past, present and future. In R. Kitchin (Ed.), *Routledge*. Routledge. https://doi.org/10.4324/9781315812281

Friedman, A., & Kohler, B. (2003). Bidimensional Regression: Assessing the Configural Similarity and Accuracy of Cognitive Maps and Other Two-Dimensional Data Sets. *Psychological Methods*, *8*(4), 468–491. https://doi.org/10.1037/1082-989X.8.4.468

Gamal, O., Thakkar, S., & Roth, H. (2020). Towards Intelligent Assistive System for Visually Impaired People: Outdoor Navigation System. *2020 24th International Conference on System Theory, Control and Computing, ICSTCC 2020 - Proceedings*, 390–397. https://doi.org/10.1109/ICSTCC50638.2020.9259682

Ghaderi, V. S., Mulas, M., Pereira, V. F. S., Everding, L., Weikersdorfer, D., & Conradt, J. (2015). A wearable mobility device for the blind using retina-inspired dynamic vision sensors. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, *2015-Novem*, 3371–3374. https://doi.org/10.1109/EMBC.2015.7319115

GitHub. (2021). *YOLOv5*. GitHub. https://github.com/ultralytics/yolov5/tree/v4.0

Giudice, N. A., Guenther, B. A., Jensen, N. A., & Haase, K. N. (2020). Cognitive Mapping Without Vision: Comparing Wayfinding Performance After Learning From Digital Touchscreen-Based Multimodal Maps vs. Embossed Tactile Overlays. *Frontiers in Human Neuroscience*, *14*, 1–18. https://doi.org/10.3389/fnhum.2020.00087

Golledge, R. G., Jacobson, R. D., Kitchin, R., & Blades, M. (2000). Cognitive maps, spatial abilities and human wayfinding. *Geographical Review of Japan, Series B*, *73*(2), 93–104. https://doi.org/10.4157/grj1984b.73.93

GOULD, J., & LEWIS, C. (1985). Designing for Usability: Key Principles and What Designers Think. *Communications of the ACM*, *28*(3), 12. https://doi.org/10.3182/20100908-3-PT-3007.00035

Gual, J., Puyuelo, M., & Lloveras, J. (2014). Three-dimensional tactile symbols produced by 3D Printing: Improving the process of memorizing a tactile map key. *British Journal of Visual Impairment*, *32*(3), 263–278. https://doi.org/10.1177/0264619614540291

Guevarra, E. C., Camama, M. I. R., & Cruzado, G. V. (2018). Development of guiding cane with voice notification for visually impaired individuals. *International Journal of Electrical and Computer Engineering*, *8*(1), 104–112. https://doi.org/10.11591/ijece.v8i1.pp104-112

Guide Dogs. (2019). *How your money is helping*. https://www.guidedogs.org.uk/about-us/how-your-money-is-helping/

Gupta, R., Rao, P. V. M., Balakrishnan, M., & Mannheimer, S. (2019). Evaluating the Use of Variable Height in Tactile Graphics. *2019 IEEE World Haptics Conference, WHC 2019*, 121–126. https://doi.org/10.1109/WHC.2019.8816083

Hamzah, R., & Fadzil, M. I. M. (2017). Voice4Blind: The talking braille keyboard to assist the visual impaired users in text messaging. *Proceedings - 2016 4th International Conference on User Science and Engineering, i-USEr 2016*, 265–270. https://doi.org/10.1109/IUSER.2016.7857972

Harpe, S. E. (2015). How to analyze Likert and other rating scale data. *Currents in Pharmacy Teaching and Learning*, *7*(6), 836–850. https://doi.org/10.1016/j.cptl.2015.08.001

Harper, S., & Green, P. (2000). A Travel Flow and Mobility Framework for Visually Impaired Travellers. *International Conference on Computers Helping People with Special Needs, May*, 289–296. http://www.simonharper.info/publications/Harper2000vn.pdf

He, K., Gkioxari, G., Dollar, P., & Girshick, R. (2017). Mask R-CNN. *Proceedings of the IEEE International Conference on Computer Vision*, *2017-Octob*, 2980–2988. https://doi.org/10.1109/ICCV.2017.322

Helen, S., & Yvonne, R. (2019). INTERACTION DESIGN beyond human-computer interaction. In *WILEY* (5th ed.). Wiley.

Hersh. (n.d.). *Questionnaire on Travel for Blind and Visually Impaired People*. University of Glasgow. Retrieved July 10, 2019, from http://web.eng.gla.ac.uk/assistive/media/travel_questionnaire.doc

Hersh. (2016). Travel and Information Processing by Blind People: A New Three-Component Model. In *Glasgow University*. http://web.eng.gla.ac.uk/assistive/media/publications/travel_model.pdf

Hersh. (2020). Mental Maps and the Use of Sensory Information by Blind and Partially Sighted People. *ACM Transactions on Accessible Computing*, *13*(2), 1–32. https://doi.org/dl.acm.org

Hersh. (2022). Wearable Travel Aids for Blind and Partially Sighted People: A Review with a Focus on Design Issues. *Sensors*, *22*(14). https://doi.org/10.3390/s22145454

Hersh, & Johnson. (2008). *Assistive Technology for Visually Impaired and Blind People*. Springer. https://doi.org/10.1007/978-1-84628-867-8

Hersh, & Johnson. (2010). A robotic guide for blind people. Part 1. A multi-national survey of the attitudes, requirements and preferences of potential end-users. *Applied Bionics and Biomechanics*, *7*(4), 277–288. https://doi.org/10.1080/11762322.2010.523626

Hersh, & Ramirez. (2022). Route Descriptions, Spatial Knowledge and Spatial Representations of Blind and Partially Sighted People: Improved Design of Electronic Travel Aids. *ACM Transactions on Accessible Computing*, *15*(4), 1–46.

Hersh, & Ramírez. (2018). Evaluation of the electronic long cane: improving mobility in urban environments. *Behaviour and Information Technology*, *37*(12), 1203–1223. https://doi.org/10.1080/0144929X.2018.1490454

Hinderks, A., Schrepp, M., & Thomaschewski, J. (n.d.). *User Experience Questionnaire (UEQ)*. Retrieved July 25, 2022, from https://www.ueq-online.org/

*How to Convert YOLOv4 Weights to TensorFlow*. (2020). Learn Data Science Using Python. https://dsbyprateekg.blogspot.com/2020/06/how-to-convert-your-yolov4-weights-to.html

Hwang, W., & Salvendy, G. (2010). Number of people required for usability evaluation: The 10±2 rule. *Communications of the ACM*, *53*(5), 130–133. https://doi.org/10.1145/1735223.1735255

Isaksson, J., Jansson, T., & Nilsson, J. (2020a). Audomni : Super-Scale Sensory Supplementation to Increase the Mobility of Blind and Low-Vision Individuals — A Pilot Study. *IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING*, *28*(5), 1187–1197.

Isaksson, J., Jansson, T., & Nilsson, J. (2020b). Desire of Use: A Hierarchical Decomposition of Activities and its Application on Mobility of by Blind and Low-Vision Individuals. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *28*(5), 1146–1156. https://doi.org/10.1109/TNSRE.2020.2985616

Islam, M. M., Sadi, M. S., Zamli, K. Z., & Ahmed, M. M. (2019). Developing Walking Assistants for Visually Impaired People: A Review. *IEEE Sensors Journal*, *19*(8), 2814–2828. https://doi.org/10.1109/JSEN.2018.2890423

ISO 9241-210:2019. (2019). *Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems*. International Standardization Organization (ISO), Switzerland. https://www.iso.org/obp/ui/#iso:std:iso:9241:-210:ed-2:v1:en

Isomursu, P., Virkkula, M., Niemelä, K., Juntunen, J., & Kumpuoja, J. (2020). Modified AttrakDiff in UX Evaluation of a Mobile Prototype. *ACM International Conference Proceeding Series*, *November*, 1–4. https://doi.org/10.1145/3399715.3399930

Jafri, R., Campos, R. L., Ali, S. A., & Arabnia, H. R. (2017). Visual and Infrared Sensor Data-Based Obstacle Detection for the Visually Impaired Using the Google Project Tango Tablet Development Kit and the Unity Engine. *IEEE Access*, *6*, 443–454. https://doi.org/10.1109/ACCESS.2017.2766579

Jafri, R., & Khan, M. M. (2018). User-centered design of a depth data based obstacle detection and avoidance system for the visually impaired. *Human-Centric Computing and Information Sciences*, *8*(1). https://doi.org/10.1186/s13673-018-0134-9

Jain, S., & Gruteser, M. (2019). Recognizing Textures with Mobile Cameras for Pedestrian Safety Applications. *IEEE Transactions on Mobile Computing*, *18*(8), 1911–1923. https://doi.org/10.1109/TMC.2018.2868659

Jiang, Z., Zhao, L., Shuaiyang, L. I., & Yanfei, J. I. A. (2020). Real-time object detection method for embedded devices. *ArXiv*, *3*, 1–11.

John Brooke. (1996). SUS - A quick and dirty usability scale. *Usability Evaluation in Industry*, 189–194.

Johnson, M. (1987). *The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason*. The University of Chicago Press.

Johnston, A. (2013). *Sensory Augmentation for Navigation in Difficult Urban Environments by People With Visual Impairment*. The Open University.

Kalach, G. G., & Kalach, G. P. (2019). Navigation system based on the fuzzy logic expert system. *International Journal of Advanced Trends in Computer Science and Engineering*, *8*(6), 2693–2698. https://doi.org/10.30534/ijatcse/2019/02862019

Kameswaran, V., Fiannaca, A. J., Kneisel, M., Karlson, A., Cutrell, E., & Morris, M. R. (2020). Understanding In-Situ Use of Commonly Available Navigation Technologies by People with Visual Impairments. *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '20)*, 1–12.

Kandel, E. R., Dudai, Y., & Mayford, M. R. (2014). The molecular and systems biology of memory. *Cell*, *157*(1), 163–186. https://doi.org/10.1016/j.cell.2014.03.001

Kaptein, M. C., Nass, C., & Markopoulos, P. (2010). Powerful and consistent analysis of likert-type rating scales. *Conference on Human Factors in Computing Systems - Proceedings*, *4*(March 2016), 2391–2394. https://doi.org/10.1145/1753326.1753686

Kaul, O. B., & Rohs, M. (2018). Requirements of navigation support systems for people with visual impairments. *UbiComp/ISWC 2018 - Adjunct Proceedings of the 2018 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2018 ACM International Symposium on Wearable Computers*, 680–683. https://doi.org/10.1145/3267305.3267685

Kaur, J., & Singh, W. (2022). Tools, techniques, datasets and application areas for object detection in an image: a review. *Multimedia Tools and Applications*, *81*, 38297–38351. https://doi.org/10.1007/s11042-022-13153-y

Kay, L. (1980). The Sonicguide;M Long Cane, and Dog Guide: Their Compatibility Leslie Kay, Ph.D. *Journal of Visual Impairment & Blindness*, *74*(7), 277–279. https://doi.org/https://doi.org/10.1177/0145482X80074007

Khan, N. S., Kundu, S., Al Ahsan, S., Sarker, M., & Islam, M. N. (2018). An Assistive System of Walking for Visually Impaired. *International Conference on Computer, Communication, Chemical, Material and Electronic Engineering, IC4ME2 2018*, 1–4. https://doi.org/10.1109/IC4ME2.2018.8465669

Kitchin, R. (2015). Cognitive Maps. *International Encyclopedia of the Social & Behavioral Sciences: Second Edition*, *November*, 79–83. https://doi.org/10.1016/B978-0-08-097086-8.72008-3

Kitchin, R., & Blades, M. (2002). The Cognition of Geographic Space. In *I.B. Tauris*.

Korthals, T., Kragh, M., Christiansen, P., Karstoft, H., Jørgensen, R., & Rückert, U. (2018). Multi-Modal Detection and Mapping of Static and Dynamic Obstacles in Agriculture for Process Evaluation. *Frontiers in Robotics and AI*, *5*(March). https://doi.org/10.3389/frobt.2018.00028

Koukourikos, P., & Papadopoulos, K. (2015). Development of Cognitive Maps by Individuals with Blindness Using a Multisensory Application. *Procedia Computer Science*, *67*, 213–222. https://doi.org/10.1016/j.procs.2015.09.265

*KR-Vision Technology*. (n.d.). Retrieved October 25, 2019, from http://krvision.cn/

Kunta, V., Tuniki, C., & Sairam, U. (2020). Multi-functional blind stick for visually impaired people. *Proceedings of the 5th International Conference on Communication and Electronics Systems, ICCES 2020*, *Icces*, 895–899. https://doi.org/10.1109/ICCES48766.2020.09137870

Kuriakose, B., Shrestha, R., & Sandnes, F. E. (2020a). Multimodal navigation systems for users with visual impairments—a review and analysis. *Multimodal Technologies and Interaction*, *4*(4), 1–19. https://doi.org/10.3390/mti4040073

Kuriakose, B., Shrestha, R., & Sandnes, F. E. (2020b). Tools and Technologies for Blind and Visually Impaired Navigation Support: A Review. *IETE Technical Review (Institution of Electronics and Telecommunication Engineers, India)*, *39*(1), 3–18. https://doi.org/10.1080/02564602.2020.1819893

Lawshe, C. H. (1975). A Quantitative Approach To Content Validity. *Personnel Psychology*, *28*(4), 563–575. https://doi.org/10.1111/j.1744-6570.1975.tb01393.x

Lazar, J., Feng, J. H., & Hochheiser, H. (2017). *Research Methods in Human-Computer Interaction* (2nd Ed.). Elsevier. https://doi.org/10.1016/b978-044481862-1/50075-3

*Lazarillo App*. (n.d.). Retrieved July 28, 2021, from https://lazarillo.app/

Lewis, J. R. (1995). IBM Computer Usability Satisfaction Questionnaires : Psychometric Evaluation and Instructions for Use. *International Journal Human-Computer Interaction*, *7*(May), 57–78.

Li, B., Munoz, J. P., Rong, X., Chen, Q., Xiao, J., Tian, Y., Arditi, A., & Yousuf, M. (2019). Vision-Based Mobile Indoor Assistive Navigation Aid for Blind People. *IEEE Transactions on Mobile Computing*, *18*(3), 702–714. https://doi.org/10.1109/TMC.2018.2842751

Li, G., Xu, J., Li, Z., Chen, C., & Kan, Z. (2022). Sensing and Navigation of Wearable Assistance Cognitive Systems for the Visually Impaired. *IEEE Transactions on Cognitive and Developmental Systems*, *15*(1), 122–133. https://doi.org/10.1109/TCDS.2022.3146828

Likert, R. (1932). A Technique for the Measurement of Attitudes. *Archives of Psychology*, *22*, 2–55. https://doi.org/10.4135/9781412961288.n454

Lin, B. S., Lee, C. C., & Chiang, P. Y. (2017). Simple smartphone-based guiding system for visually impaired people. *Sensors (Switzerland)*, *17*(6). https://doi.org/10.3390/s17061371

Lincoln, Y., & Guba, E. (1985). *Naturalistic inquiry*. Thousand Oaks, CA : Sage.

Lloyd, R. (1989). Cognitive Maps: Encoding and Decoding lnformation. *Annals of the Association of American Geographers*, *79*(1), 101–124.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual Navigation by Blind and Sighted: Assessment of Path Integration Ability. *Journal of Experimental Psychology: General*, *122*(1), 73–91. https://doi.org/10.1037/0096-3445.122.1.73

Loomis, J. M., Klatzky, R. L., Lippa, Y., & Golledge, R. G. (2002). Spatial Updating of Locations Specified by 3-D Sound and Spatial Language. *Journal of Experimental Psychology: Learning Memory and Cognition*, *28*(2), 335–345. https://doi.org/10.1037/0278-7393.28.2.335

LYNN, M. (1986). Determination and Quantification Of Content Validity. *Nursing Research*, *35*(6), 382–386.

*Malaysia Association for the Blind (MAB)*. (n.d.). MAB. Retrieved January 24, 2023, from https://www.mab.org.my/

Malkawi, A., Kamaruddin, A., Halin, A., & Admodisastro, N. (2023). Listening to the Voice of People with Vision Impairment. *International Journal of Advanced Computer Science and Applications (IJACSA)*, *14*(4), 414–423. https://doi.org/10.14569/IJACSA.2023.0140446

Manduchi, R., & Kurniawan, S. (2011). Mobility-related accidents experienced by people with visual impairment. *Insight: Research and Practice in Visual Impairment and Blindness*, *4*(2), 44–54.

Manduchi, R., Kurniawan, S., & Manduchi, Roberto, S. K. (2010). Watch Your Head, Mind Your Step: Mobility-Related Accidents Experienced by People with Visual Impairment. *Tech. Rep., Department of Computer Engineering, University of California, Santa Cruz, CA, USA*, 1–11. http://www.soe.ucsc.edu/research/technical-reports/UCSC-SOE-10-24%0Ahttps://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=Watch+Your+Head%2C+Mind+Your+Step%3A+Mobility-Related+Accidents+Experienced+by+People+with+Visual+Impairment&btnG=%0Ahttps://www.s

*Mann Whitney U test calculator (Wilcoxon rank-sum)*. (n.d.). Statistics Kingdom. Retrieved October 19, 2022, from https://www.statskingdom.com/170median_mann_whitney.html

Marston, J. R., & Church, R. L. (2005). A relative access measure to identify barriers to efficient transit use by persons with visual impairements. *Disability and Rehabilitation*, *27*(13), 769–779. https://doi.org/10.1080/09638280400014790

Martinez-Alpiste, I., Casaseca-De-La-Higuera, P., Alcaraz-Calero, J., Grecos, C., & Wang, Q. (2019). Benchmarking Machine-Learning-Based Object Detection on a UAV and Mobile Platform. *IEEE Wireless Communications and Networking Conference, WCNC*, *2019-April*, 1–6. https://doi.org/10.1109/WCNC.2019.8885504

Martinez-Alpiste, I., Golcarenarenji, G., Wang, Q., & Alcaraz-Calero, J. M. (2022). Smartphone-based real-time object recognition architecture for portable and constrained systems. *Journal of Real-Time Image Processing*, *19*(1), 103–115. https://doi.org/10.1007/s11554-021-01164-1

Martinez-Cruz, S., Morales-Hernandez, L. A., Perez-Soto, G. I., Benitez-Rangel, J. P., & Camarillo-Gomez, K. A. (2021). An Outdoor Navigation Assistance System for Visually Impaired People in Public Transportation. *IEEE Access*, *9*, 130767–130777. https://doi.org/10.1109/ACCESS.2021.3111544

Mathew, A., Amudha, P., & Sivakumari, S. (2021). Deep Learning Techniques: An Overview. *Advances in Intelligent Systems and Computing*, *1141*, 599–608. https://doi.org/10.1007/978-981-15-3383-9_61

Meenakshi, R., Ponnusamy, R., Alghamdi, S., Ibrahim Khalaf, O., & Alotaibi, Y. (2022). Development of Mobile App to Support the Mobility of Visually Impaired People. *Computers, Materials & Continua*, *73*(2), 3473–3495. https://doi.org/10.32604/cmc.2022.028540

Meng, X.-L., Rosenthal, R., & Rubin, D. B. (1992). Comparing Correlated Correlation Coefficients. *Psychological Bulletin*, *111*(1), 172–175. http://psycnet.apa.org/journals/bul/111/1/172/

Merriam, S. (2009). *Qualitative Research A Guide to Design and Implementation* (2nd ed.). Jossey-Bass.

Meza-de-Luna, M., Terven, J., Raducanu, B., & Salas, J. (2019). A Social-Aware Assistant to support individuals with visual impairments during social interaction: A systematic requirements analysis. *International Journal of Human Computer Studies*, *122*(August 2017), 50–60. https://doi.org/10.1016/j.ijhcs.2018.08.007

Mondada, L. (2008). Qualitative Data Transcription and Translation. *International Rescue Committee*, 127–131.

*Moovit App*. (n.d.). Retrieved July 28, 2021, from https://moovit.com

Mortensen, D. H. (2020). *How to Do a Thematic Analysis of User Interviews*. Interaction Design Foundation. https://www.interaction-design.org/literature/article/how-to-do-a-thematic-analysis-of-user-interviews

Muhammad, Y., Jan, M. A., Mastorakis, S., & Zada, B. (2022). A Deep Learning-Based Smart Assistive Framework for Visually Impaired People. *2022 IEEE International Conference on Omni-Layer Intelligent Systems, COINS 2022*. https://doi.org/10.1109/COINS54846.2022.9854984

Myers, J. L., & Arnold D., W. (2003). *Research Design and Statistical Analysis* (2nd ed.). Lawrence Erlbaum Associates.

Nair, V., Ma, S. E., Gonzalez Penuela, R. E., He, Y., Lin, K., Hayes, M., Huddleston, H., Donnelly, M., & Smith, B. A. (2022). Uncovering Visually Impaired Gamers' Preferences for Spatial Awareness Tools Within Video Games. In *ASSETS 2022 - Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility* (Vol. 1, Issue 1). Association for Computing Machinery. https://doi.org/10.1145/3517428.3544802

Nair, V., Olmschenk, G., Seiple, W. H., & Zhu, Z. (2022). ASSIST: Evaluating the usability and performance of an indoor navigation assistant for blind and visually impaired people. *Assistive Technology*, *34*(3), 289–299. https://doi.org/10.1080/10400435.2020.1809553

Narlagiri, S. (2020). Development of Blind Assistive Device in Shopping Malls. *Journal of Mechanics of Continua and Mathematical Sciences*, *15*(9), 5–7. https://doi.org/10.26782/jmcms.2020.09.00021

Nawrocka-Łabuś, K. (2017). Spatial Orientation in Children: A Tyflological Approach. In *Mobility of Visually Impaired People* (pp. 263–282). Springer. https://doi.org/https://doi.org/10.1007/978-3-319-54446-5_9

Nazareth, A., Weisberg, S. M., Margulis, K., & Newcombe, N. S. (2018). Charting the development of cognitive mapping. *Journal of Experimental Child Psychology*, *170*, 86–106. https://doi.org/10.1016/j.jecp.2018.01.009

Nicholls, M. E. R. (2010). Likert Scales. *The Corsini Encyclopedia of Psychology, Wiley Online Library*. https://doi.org/https://doi.org/10.1002/9780470479216.corpsy0508

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *International Journal of Qualitative Methods*, *16*(1), 1–13. https://doi.org/10.1177/1609406917733847

*NVIVO*. (n.d.). Retrieved April 10, 2021, from https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

O'Keefe, J., & Nadel, L. (1978). The Hippocampus as a Cognitive Map. In *Philosophical Studies* (Vol. 27). https://doi.org/10.5840/philstudies19802725

Ohn-Bar, E., Guerreiro, J., Ahmetovic, D., Kitani, K. M., & Asakawa, C. (2018). Modeling expertise in assistive navigation interfaces for blind people. *IUI '18: 23rd International Conference on Intelligent User Interfaces*, 403–407. https://doi.org/10.1145/3172944.3173008

Ohn-Bar, E., Kitani, K., & Asakawa, C. (2018). Personalized dynamics models for adaptive assistive navigation systems. *2nd Conference on Robot Learning (CoRL 2018).*

Ohuchi, M., Iwaya, Y., & Munekata, T. (2006). Cognitive-Map Formation of Blind Persons in a Virtual Sound Environment. *Special Education*, 1–7.

*Otter.ai*. (n.d.). Retrieved February 2, 2023, from https://otter.ai/?irclickid=Uq-2OaRPMxyNUbNxYZUTMz9RUkA33wWha2p%3AW40&irgwc=1&utm_term=1113693&utm_medium=tracking_link&utm_source=affiliate&utm_content=other

Ottink, L., Buimer, H., van Raalte, B., Doeller, C., van der Geest, T., & van Wezel, R. (2022). Cognitive map formation supported by auditory, haptic, and multimodal information in persons with blindness. *Neuroscience and Biobehavioral Reviews*, *140*(104797), 1–13. https://doi.org/10.1016/j.neubiorev.2022.104797

Ottink, L., van Raalte, B., Doeller, C., Van der Geest, T., & Van Wezel, R. (2022). Cognitive map formation through tactile map navigation in visually impaired and sighted persons. *Scientific Reports, 12*(11567), 1–15. https://doi.org/10.1038/s41598-022-15858-4

Ozok, A. (2008). Survey design and implementation in HCI. In *The Human-Computer Interaction Handbook* (2nd ed., pp. 1151–1169). Lawrence Erlbaum Associates.

Palivcová, D., Macík, M., & Míkovec, Z. (2020). Interactive tactile map as a tool for building spatial knowledge of visually impaired older adults. *CHI'20*. https://doi.org/10.1145/3334480.3382912

Patel, S., Kumar, A., Yadav, P., Desai, J., & Patil, D. (2018). Smartphone-based obstacle detection for visually impaired people. *Proceedings of 2017 International Conference on Innovations in Information, Embedded and Communication Systems, ICIIECS 2017*, *2018-January*, 1–3. https://doi.org/10.1109/ICIIECS.2017.8275916

Patton, M. (2014). *Qualitative research & evaluation methods : integrating theory and practice* (4th ed.). SAGE Publications, Inc.

Payne, S. J. (2003). HCI Models, Theories, and Frameworks: Toward a multidisciplinary science. In *HCI Models, Theories, and Frameworks: Toward a Multidisciplinary Science*. Morgan Kaufmann. https://doi.org/10.1016/B978-155860808-5/50006-X

Pearson, J., Naselaris, T., Holmes, E. A., & Kosslyn, S. M. (2015). Mental Imagery: Functional Mechanisms and Clinical Applications. *Trends in Cognitive Sciences*, *19*(10), 590–602. https://doi.org/10.1016/j.tics.2015.08.003

Pissaloux, E., & Velázquez, R. (2017). *Mobility of Visually Impaired People*. Springer International Publishing. https://doi.org/10.1007/978-3-319-54446-5

Pissaloux, E., Velazquez, R., & Maingreaud, F. (2017). A New Framework for Cognitive Mobility of Visually Impaired Users in Using Tactile Device. *IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS*, *47*(6), 1040–1051.

Pissaloux, Velazquez, Hersh, & Uzan. (2017). Towards a Cognitive Model of Human Mobility : An Investigation of Tactile Perception for use in Mobility Devices. *THE JOURNAL OF NAVIGATION*, *70*, 1–17. https://doi.org/10.1017/S0373463316000461

Polit, D., & Beck, C. T. (2006). The Content Validity Index: Are You Sure You Know What's Being Reported? Critique and Recommendations. *Research in Nursing & Health*, *29*, 489–497.

Ponnada, S., Yarramalle, S., & Madhusudhana Rao, T. V. (2018). A hybrid approach for identification of manhole and staircase to assist visually challenged. *IEEE Access*, *6*, 41013–41022. https://doi.org/10.1109/ACCESS.2018.2852723

Quiñones, P., Greene, T., Yang, R., & Newman, M. (2011). Supporting Visually Impaired Navigation : A Needs-finding Study. *CHI'11*. 978-1-4503-0268-5/ 11/ 05.

Qureshi, H. H., & Wong, D. H. Ten. (2019). Requirements of a Mobile Application Design Model for Visually Impaired People. *Open International Journal of Informatics*, *7*(2), 96–104.

Rabionet, S. E. (2011). How I learned to design and conduct semi-structured interviews: An ongoing and continuous journey. *Qualitative Report*, *16*(2), 563–566.

Rachburee, N., & Punlumjeak, W. (2021). An assistive model of obstacle detection based on deep learning: YOLOv3 for visually impaired people. *International Journal of Electrical and Computer Engineering*, *11*(4), 3434–3442. https://doi.org/10.11591/ijece.v11i4.pp3434-3442

Rallis, S., & Rossman, G. (2012). *The Research Journey: Introduction to Inquiry*. The Guilford Press.

Ramadhan, A. J. (2018). Wearable smart system for visually impaired people. *Sensors*, *18*, 843. https://doi.org/10.3390/s18030843

Real, S., & Araujo, A. (2019). Navigation systems for the blind and visually impaired: Past work, challenges, and open problems. *Sensors (Switzerland)*, *19*(15). https://doi.org/10.3390/s19153404

Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You only look once: Unified, real-time object detection. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, *2016-Decem*, 779–788. https://doi.org/10.1109/CVPR.2016.91

Renzi, C., Cattaneo, Z., Vecchi, T., & Cornoldi, C. (2013). Mental Imagery and Blindness. In *Multisensory Imagery* (pp. 115–130). Springer.

Rey-Galindo, J. A., Rizo-Corona, L., González-Muñoz, E. L., & Aceves-González, C. (2020). Environmental information for people with visual impairment in Mexico - or what they need and how they use it. *Applied Ergonomics*, *85*(103079). https://doi.org/10.1016/j.apergo.2020.103079

Rishi, S., Subbalakhmi, C., & Saini, H. S. (2020). Mobile App Accessibility for Visually Impaired. *International Journal of Advanced Trends in Computer Science and Engineering*, *9*(1), 182–185. http://www.warse.org/IJATCSE/static/pdf/file/ijatcse27912020.pdf

*Roboflow*. (2021). https://roboflow.com/

Santos, A. D. P., Medola, F. O., Cinelli, M. J., Garcia Ramirez, A. R., & Sandnes, F. E. (2021). Are electronic white canes better than traditional canes? A comparative study with blind and blindfolded participants. *Universal Access in the Information Society*, *20*, 93–103. https://doi.org/10.1007/s10209-020-00712-z

Sapp, W. (2010). Visual Impairment. In *International Encyclopedia of Education* (3rd ed., pp. 880–885). ScienceDirect. https://doi.org/10.1016/B978-0-08-044894-7.01108-8

Seifert, K., & Sutton, R. (2011). *Educational Psychology* (3rd Ed.). Jacob Foundation.

Senjam, S. S., Manna, S., & Bascaran, C. (2021). Smartphones-based assistive technology: Accessibility features and apps for people with visual impairment, and its usage, challenges, and usability testing. *Clinical Optometry*, *13*, 311–322. https://doi.org/10.2147/OPTO.S336361

Shakeel, H. (2020). *Tensorflow-yolov4-tflite*. GitHub. https://github.com/haroonshakeel/tensorflow-yolov4-tflite

Shimakawa, M., Matsushita, K., Taguchi, I., Okuma, C., & Kiyota, K. (2019). Smartphone apps of obstacle detection for visually impaired and its evaluation. *ACM International Conference Proceeding Series*, 143–148. https://doi.org/10.1145/3325291.3325381

Shingledecker, C. A., & Foulke, E. (1978). A Human Factors Approach to the Assessment of the Mobility of Blind Pedestrians. *Human Factors: The Journal of Human Factors and Ergonomics Society*, *20*(3), 273–286. https://doi.org/10.1177/001872087802000303

Silver, N. C., & Dunlap, W. P. (1987). Averaging Correlation Coefficients: Should Fisher's z Transformation Be Used? *Journal of Applied Psychology*, *72*(1), 146–148. https://doi.org/10.1037/0021-9010.72.1.146

Sim, W. C. S. S., Silva, Y. M. L. R., Pio, L. D. S., Jazdi, N., & Jr, V. F. D. L. (2019). Audio Guide for Visually Impaired People Based on Combination of Stereo Vision and Musical Tones. *Sensors*, *20*, 151. https://doi.org/10.3390/s20010151

Sisman, E. E. (2013). Pedestrian Zones. In *Advances in Landscape Architecture*. IntechOpen. https://doi.org/10.5772/51738

Smith, A., I'Aune, W. D., & Geruschat. (1992). Low vision mobility problems: perceptions of O&M Specialists and Persons with Low Vision. *Journal of Visual Impairment & Blindness*, *86*(1).

Spagnol, S., Wersényi, G., Bujacz, M., Bslan, O., Martínez, M. H., Moldoveanu, A., & Unnthorsson, R. (2018). Current use and future perspectives of spatial audio technologies in electronic travel aids. *Wireless Communications and Mobile Computing*, *2018*. https://doi.org/10.1155/2018/3918284

Spiers, H. J. (2016). Spatial Cognition : Finding the Boundary in the Occipital Place Area. *Current Biology*, *26*(8), R323–R325. https://doi.org/10.1016/j.cub.2016.02.049

Spradley, J. (1980). *Participant observation*. New York: Holt, Rinehart and Winston.

Straub, D., & Gefen, D. (2004). Validation Guidelines for IS Positivist Research. *Communications of the Association for Information Systems*, *13*(January). https://doi.org/10.17705/1cais.01324

Stufflebeam, D., Madaus, G., & Kellaghan, T. (2000). *Evaluation Models: Viewpoints on Educational and Human Services Evaluation*. Kluwer Academic Publishers.

Sullivan, G. M., & Artino, A. R. (2013). Analyzing and Interpreting Data From Likert-Type Scales. *Journal of Graduate Medical Education*, *5*(4), 541–542. https://doi.org/10.4300/jgme-5-4-18

*SUMI - Software Usability Measurement Inventory*. (n.d.). Retrieved November 26, 2022, from https://sumi.uxp.ie/index.html

Summerfield, M. (2013). Global Geomorphology. In *Routledge* (Third). Routledge. https://doi.org/10.1017/CBO9781107415324.004

Sun, C., Su, J., Shi, Z., & Guan, Y. (2019). P-Minder: A CNN Based Sidewalk Segmentation Approach for Phubber Safety Applications. *IEEE International Conference on Image Processing (ICIP)*, 4160–4164. https://doi.org/10.1109/icip.2019.8803417

Tachiquin, R., Vel, R., Del-valle-soto, C., Guti, C. A., Carrasco, M., Fazio, R. De, Visconti, P., & Vidal-verd, F. (2021). Wearable Urban Mobility Assistive Device for Visually Impaired Pedestrians Using a Smartphone and a Tactile-Foot Interface. *Sensors*, *21*, 5274.

Taherdoost, H. (2016). Validity and Reliability of the Research Instrument ; How to Test the Validation of a Questionnaire / Survey in a Research. *International Journal of Academic Research in Management*, *5*(3), 28–36.

Tan, J. K., Ishimine, T., & Arimasu, S. (2019). Walk environment analysis using my vision: Toward a navigation system providing visual assistance. *International Journal of Innovative Computing, Information and Control*, *15*(3), 861–871. https://doi.org/10.24507/ijicic.15.03.861

Tapu, R., Mocanu, B., & Zaharia, T. (2020). Wearable assistive devices for visually impaired: A state of the art survey. *Pattern Recognition Letters*, *137*, 37–52. https://doi.org/10.1016/j.patrec.2018.10.031

*Technique*. (n.d.). Retrieved February 7, 2023, from https://www.oxfordlearnersdictionaries.com/definition/english/technique

Techzizou. (2021). *YOLOv4-Tiny Custom Training*. GitHub. https://github.com/techzizou/yolov4-tiny-custom_Training

*TensorFlow 2 Object Detection API tutorial*. (n.d.). Retrieved January 5, 2021, from https://tensorflow-object-detection-api-tutorial.readthedocs.io/en/latest/index.html

*TensorFlow Core*. (2022). TensorFlow. https://www.tensorflow.org/guide/core#:~:text=The TensorFlow Core APIs provide,frameworks within the TensorFlow platform.

*Terrain*. (n.d.). Wikipedia. Retrieved September 13, 2019, from https://en.wikipedia.org/wiki/Terrain#References

*Terrain Avoidance and Warning System*. (n.d.). Sky Brary. Retrieved August 15, 2019, from https://skybrary.aero/index.php/Terrain_Avoidance_and_Warning_System_(TAWS)

Terven, J. R., Salas, J., & Raducanu, B. (2014). New Opportunities for computer vision-based assistive technology systems for the visually impaired. *Computer*, *47*(4), 52–58. https://doi.org/10.1109/MC.2013.265

Tobler, W. R. (1994). Bidimensional Regression. *Geographical Analysis*, *26*(3), 187–212. https://doi.org/10.1111/j.1538-4632.1994.tb00320.x

Tolman, E. C. (1948). Cognitive maps in rats and men. *Image and Environment: Cognitive Mapping and Spatial Behavior*, 27–50. https://doi.org/10.4324/9780203789155-11

Tversky, B. (2000). Levels and structure of spatial knowledge. In R. Kitchin (Ed.), *Cognitive Mapping: Past, Present and Future* (pp. 24–43). Taylor & Francis.

Uzan G, Hanse P-C, Seck M, W. P. (2015). Solid: a model of the principles, processes and information required to ensure mobility for all in public transport systems. *19th Triennial Congress of the International Ergonomics Association (IEA).*

Valipoor, M., & Antonio, A. de. (2022). Recent trends in computer vision-driven scene understanding for VI/ blind users: a systematic mapping. *Universal Access in the Information Society*, *22*, 983–1005.

Van Der Bie, J., Jaschinski, C., & Allouch, S. Ben. (2019). Sidewalk, a wayfinding message syntax for people with a visual impairment. *ASSETS 2019 - 21st International ACM SIGACCESS Conference on Computers and Accessibility*, 609–611. https://doi.org/10.1145/3308561.3354625

Varghese Jacob, S., & MacKenzie, I. S. (2018). Comparison of feedback modes for the visually impaired: Vibration vs. audio. *International Conference on Universal Access in Human-Computer Interaction (UAHCI 2018), 10907*, 420–432. https://doi.org/10.1007/978-3-319-92049-8_30

Virzi, R. A., Sokolov, J. L., & Karis, D. (1996). Usability problem identification using both low- and high-fidelity prototypes. *Conference on Human Factors in Computing Systems - Proceedings*, *January 1996*, 236–243. https://doi.org/10.1145/238386.238516

Viswanatha, V., Chandana, R., & Ramachandra, A. (2022). Real Time Object Detection System with YOLO and CNN Models: A Review. *ArXiv*. https://doi.org/10.37896/JXAT14.07/315415

Walter, E., Scaramuzza, G., Niemann, S., & Cavegn, M. (2013). *Fussverkehr*. BERATUNGSSTELLE FUER UNFALLVERHUETUNG. http://worldcat.org/isbn/9783908192947

Wang, C.-Y., Bochkovskiy, A., & Liao, H.-Y. M. (2022). YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors. *ArXiv*, *1*, 1–15. http://arxiv.org/abs/2207.02696

Wasserman, L. (2006a). All of Nonparametric Statistics. In *Springer*. Springer. https://doi.org/10.1198/tech.2007.s454

Wasserman, L. (2006b). *All of Nonparametric Statistics*. Springer.

*Waze App*. (n.d.). Retrieved July 28, 2021, from https://www.waze.com/

Wessa, P. (2023). *Cronbach alpha (v1.0.7) in Free Statistics Software (v1.2.1)*. Office for Research Development and Education. https://www.wessa.net/rwasp_cronbach.wasp/

*WeWalk*. (n.d.). Retrieved January 15, 2021, from https://wewalk.io/en/

*What is orientation and mobility*. (n.d.). Vision Australia. Retrieved February 15, 2022, from https://www.visionaustralia.org/news/2019-08-23/what-orientation-and-mobility#:~:text=But what exactly is orientation,their way through their environment.

Whittington, J., McCaffary, D., Bakermans, J., & Behrens, T. (2022). How to build a cognitive map. *Nature Neuroscience*, *25*, 1257–1272. https://www.nature.com/articles/s41593-022-01153-y

WHO. (n.d.). *Disabilities*. Retrieved March 29, 2019, from https://www.who.int/topics/disabilities/en/

WHO. (2022). *Blindness and Vision Impairment*. https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

Williams, M. A., Galbraith, C., Kane, S. K., & Hurst, A. (2014). Just Let the Cane Hit It : How the Blind and Sighted See Navigation Differently. *16th International ACM SIGACCESS Conference on Computers & Accessibility*, 217–224.

Williams, M. A., Hurst, A., & Kane, S. K. (2013). Pray Before You Step Out: Describing Personal and Situational Blind Navigation Behaviors. *15th International ACM SIGACCESS Conference on Computers and Accessibility*, 1–8. http://dx.doi.org/10.1145/2513383.2513449

Wohlin, C., Runeson, P., Ohlsson, M., & C., M. (2012). Experimentation in Software Engineering. In *Https://Medium.Com/*. Springer. https://medium.com/@arifwicaksanaa/pengertian-use-case-a7e576e1b6bf

World Access for the Blind. (n.d.). *Blindness: Challenge and Achievement*. World Access for the Blind. Retrieved December 1, 2018, from https://waftb.net/blindness-challenge-and-achievement

Yaagoubi, R., Edwards, G., Badard, T., & Mostafavi, M. A. (2012). Enhancing the mental representations of space used by blind pedestrians, based on an image schemata model. *Cognitive Processing*, *13*(4), 333–347. https://doi.org/10.1007/s10339-012-0523-3

Yadav, S., Joshi, R. C., Dutta, M. K., Kiac, M., & Sikora, P. (2020). Fusion of Object Recognition and Obstacle Detection approach for Assisting Visually Challenged Person. *2020 43rd International Conference on Telecommunications and Signal Processing, TSP 2020*, 537–540. https://doi.org/10.1109/TSP49548.2020.9163434

Yang, K., Bergasa, L. M., Romera, E., Cheng, R., Chen, T., & Wang, K. (2018). Unifying terrain awareness through real-time semantic segmentation. *IEEE Intelligent Vehicles Symposium (IV)*, 1033–1038.

Yang, K., Wang, K., Bergasa, L., Romera, E., Weijian, H., Sun, D., Sun, J., Cheng, R., Chen, T., & López, E. (2018). Unifying Terrain Awareness for the Visually Impaired through Real-Time Semantic Segmentation. *Sensors*, *18*, 1506. https://doi.org/10.3390/s18051506

Yang, R., Park, S., Mishra, S. R., Hong, Z., Newsom, C., Joo, H., Hofer, E., & Newman, M. W. (2011). Supporting spatial awareness and independent wayfinding for pedestrians with visual impairments. *ASSETS'11: Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*, 27–34. https://doi.org/10.1145/2049536.2049544

*YOLOv5 CoLab*. (n.d.). GitHub. Retrieved August 25, 2020, from https://colab.research.google.com/github/ultralytics/yolov5/blob/master/tutorial.ipynb

Yong, S. P., & Yeong, Y. C. (2018). Human Object Detection in Forest with Deep Learning based on Drone's Vision. *2018 4th International Conference on Computer and Information Sciences (ICCOINS)*. https://doi.org/10.1109/ICCOINS.2018.8510564

Yusoff, M. S. B. (2019). ABC of Content Validation and Content Validity Index Calculation. *Education in Medicine Journal*, *11*(2), 49–54. https://doi.org/10.21315/eimj2019.11.2.6

Zeng, L. (2015). A survey: Outdoor mobility experiences by the visually impaired. *Mensch Und Computer 2015 - Workshop*, 391–398. https://doi.org/10.1515/9783110443905-056

Zhang, X., Yao, X., Zhu, Y., & Hu, F. (2019). An ARCore based user centric assistive navigation system for visually impaired people. *Applied Sciences (Switzerland)*, *9*(5). https://doi.org/10.3390/app9050989

Zhao, L., Wang, L., Jia, Y., & Cui, Y. (2022). A lightweight deep neural network with higher accuracy. *PLOS ONE*, *17*(8). https://doi.org/10.1371/journal.pone.0271225

Zhao, Y., Kupferstein, E., Castro, B. V., Feiner, S., & Azenkot, S. (2019). Designing AR visualizations to facilitate stair navigation for people with low vision. *UIST '19 - Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, 387–402. https://doi.org/https://doi.org/10.1145/3332165.3347906

Zhao, Y., Kupferstein, E., Tal, D., & Azenkot, S. (2018). It looks beautiful but scary: How low vision people navigate stairs and other surface level changes. *ASSETS '18 - Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility*, 307–320. https://doi.org/10.1145/3234695.3236359

Zilbershtain-Kra, Y., Graffi, S., Ahissar, E., & Arieli, A. (2021). Active sensory substitution allows fast learning via effective motor-sensory strategies. *IScience*, *24*(1), 101918. https://doi.org/10.1016/j.isci.2020.101918