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Virtual World Navigation Hat – Development of Visual Sensory Substitution Device

through Point Cloud Projection and IoT services for the Visually Impaired

An Undergraduate Design Project Presented to Faculty of the

Computer Engineering Department College of Technology

University of San Agustin

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INTRODUCTION

Background of the Study

Visual impairment is a global health problem that significantly affects individuals' daily lives by impeding independent navigation, social interaction, and overall quality of life (Theodorou et al., 2023). There is an estimation of 2.2 billion people globally who are identified as visually impaired and this number could still increase to 2.5 billion by 2050 as stated by the World Health Organization (WHO) (2023). In the Philippines, 2.17 million Filipinos are identified as visually impaired as quantized by reports from the Philippines Eye Research Institute (PERI) and Department of Health (DOH) (Shinagawa Lasik Center, 2025). (Insert stats for iloilo city once retrieved). Visual impairment does not pertain to total blindness. According to WHO (2023), visual impairment can be identified and categorized based on the presenting visual acuity a) Mild Vision Impairment, visual acuity is better than 6/18, b) Moderate Vision Impairment, visual acuity is worse than 6/18 but better than 6/60, c) Severe Vision impairment, visual acuity is worse than 6/60 but better than 3/60, and d) Blindness, visual acuity is worse than 3/60. Blindness can be further categorized into d.1) Blindness with light perception, individuals can only perceive light and, d.2) Total Blindness, individuals who have no light perception. Other common types include astigmatism, near-sightedness (myopia) and far-sightedness (hyperopia), which account for a large share of impairments, alongside conditions like cataracts, glaucoma, and age-related macular degeneration (AMD), with AMD alone affecting 8.06 million people globally in 2021 (Yon, 2025). Visually impaired individuals face safety concerns and challenges such as accidents, falls, and collisions, as well as difficulties with



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navigation, including road crossings and destination location (Ikram et al., 2024; Gao et al., 2025; Muhsin et al., 2023). Beyond these practical difficulties, social isolation and reduced access to information further compound the challenges, often limiting educational and employment opportunities (Arvind, 2023). Current existing solutions or aid for visually impaired individuals are guide dogs, white canes, and electronic travel aids (Muhsin et al., 2023).

According to Mishra, A., Bai, Y., Narayanasamy, P., Garg, N., & Roy, N. (2025), sensory substitution devices (SSDs) are assistive technology that converts information typically perceived through one sensory modality into another, enabling individuals with sensory impairments to access environmental cues they lack. In the context of visual impairment, such devices translate visual data, such as depth or object presence, into haptic or auditory signals to assist the visually impaired in perceiving their environment (Jiayu, 2025). This intermodal conversion allows users to develop a novel form of perception, effectively substituting the impaired sense with an intact one, enhancing the understanding of the surroundings(Jiang et al., 2025). These devices could significantly enhance independence by enabling obstacle detection, navigation, and object recognition, particularly for the fully blind who rely on traditional aids like white canes or guide dogs.(Tokmurziyev et al., 2025). However, SSDs are not widely adopted globally due to challenges such as cognitive overload from processing substituted sensory data, extensive training requirements for intuitiveness, ergonomic discomfort in wearables, and processing constraints of non-visual senses like hearing or touch, which have lower bandwidth than vision (Hou et al., 2025) Discuss variables



Rationale

More than 2.17 million people in the Philippines live with visual impairment, which restricts their perception, mobility, navigation, and accessibility to information—depriving them of work opportunities and independence. Wearable SSD is an assistive technology that an individual can wear on their body to supplement a missing sense, helping users navigate both their physical surroundings and digital applications. Additionally, it promotes social interaction that aligns with one of the United Nations' Sustainable Development Goals for health and equality. Supporting local innovation by developing a low-cost, locally made device increases access to technology, thereby enhancing the technology sector.

In previous studies, SSDs have been limited in their applicability, as existing devices often perform poorly in real-world situations, encountering cognitive overload problems that overwhelm users with excessive information, making navigation difficult. Another identified concern is that the device design is uncomfortable, as it is bulky and requires extensive training, which limits its practicality. In addition, many devices lack digital integration as capabilities, focusing mainly on obstacle detection and not connecting well with digital tools. These deficiencies underscore the pressing need for higher SSDs that can outperform and enhance existing devices. Therefore, there is a need for a smart navigation hat that improves the functional efficiency and performance of SSDs. This navigation hat integrates AIoT, introducing a smart navigation hat that uses 3D point cloud data to give audio feedback and connects to IoT services for navigation in both physical and digital environments. Furthermore, it enhances sensory processing, focusing on



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reducing cognitive overload in the system and making navigation simpler for VIP users.

Additionally, the hat features customizable options, including a modular operating system that allows users to choose between gesture or voice commands.

Objectives of the Study

General Objectives

To develop an AIoT visual sensory substitution hat device that converts real-time environment information through emulating human sensory processes into audio cues for the visually impaired people (VIP)

Specific Objectives

- To develop a prototype that:
 - create a point cloud projection of the environment through the camera
 - update the virtual physical map
 - emulate human sensory process modes to generate audio cues
 - use hand gesture recognition
- To develop a program that successfully creates a point cloud projection that is matched in a virtual physical world
- To develop a program that takes in the environmental data and emulates human like sense processing to generate necessary audio cues to represent the environment with minimal sensory overload



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- To develop the system that can support multiple plugins that can insert themselves anywhere in the previous objectives processes integrated in the device and in the server

Significance of the Study

The proposed AIoT navigation hat has the potential to escalate the performance of existing assistive devices by a) enhancing independence and mobility; b) improving cognitive comfort and ease of use; c) bridging physical and digital accessibility participation; d) promoting Social Inclusion and Employment Opportunities for the VIP. In addition, this system innovates the research for Assistive Technology in the Philippines. a) VIP can navigate safely and confidently with less assistance, b) the system simplifies understanding spatial information, reducing mental strain (cognitive overload) and allowing quick interpretation without long training, c) with AIoT integration, users can access navigation apps and online services hands-free using voice or gesture commands. d) As VIP gain independence, they can engage more in education, work, and community activities, boosting their self-esteem and reducing reliance on others. The project's success may inspire further studies on brain-inspired computing and wearable assistive devices, paving the way for more innovative tools.

This project device will specifically benefit to the following:

- Visually Impaired and Blind Individuals. They are the primary beneficiaries, gaining increased mobility, safety, and access to digital and social spaces through sensory substitution and IoT assistance.



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- Families and Caregivers. With the device promoting user independence, caregivers will experience reduced physical and emotional strain while maintaining peace of mind about the user's safety.
- Educators and Accessibility Advocates. Teachers and advocates working with visually impaired students can integrate the technology into learning environments to enhance inclusivity and accessibility.
- Medical and Rehabilitation Specialists. Eye health professionals and rehabilitation centers can use the system as a tool for sensory training and mobility rehabilitation programs.
- Researchers and Engineers in Assistive Technology. The project offers a novel framework that combines virtual world modeling, IoT, and sensory emulation, providing a foundation for future innovations in human-computer interaction and embedded systems.
- Government and NGOs for Disability Support. Organizations involved in disability welfare can adopt or fund similar low-cost solutions to support national accessibility programs and meet inclusive development goals.

Conceptual Framework



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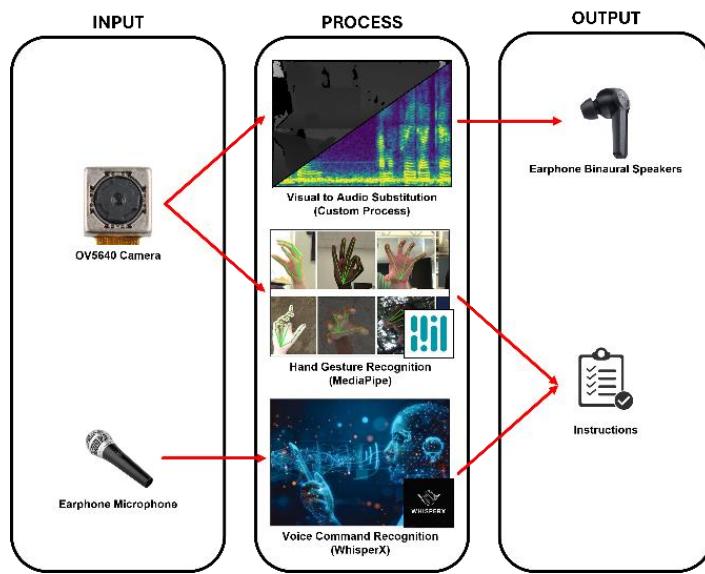


Figure 1: IPO Model of the Controlled System

The conceptual framework outlines the device's input-process-output model, incorporating variables aligned with human sensory processing. Inputs include stereo images from two OV5640 USB cameras (5MP, 160° FOV, 10cm apart, 30fps), yielding depth (disparity map) and color data via stereo computations. User orientation from the IMU (accelerometer + gyroscope) corrects for head movements. The point cloud output is scaled and mapped to a virtual digital environment using error correction from prior frames or IMU data.

Necessary information is processed: Voice data (e.g., commands, messages) is directly output to speakers; depth information becomes a spectrogram (frequency for Y-axis, binaural audio for X-axis, volume for Z-axis/depth). The focus point is centered in the user's forward view, with focus radius inversely proportional to focus change speed



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(biased on X-axis for horizontal priority; shape as a tall oval to emphasize vertical threats like steps or overhead objects). Variables emulate human theories: Logarithmic scaling filters constant movements over time; focus scoping prioritizes central depth over peripherals, reducing data volume. Outputs are audio/haptic cues via earphones, enabling navigation in physical (obstacle avoidance) and digital (app interactions) worlds.

Theoretical Framework

This research is grounded in theories of human cognitive senses, such as logarithmic scaling (Weber-Fechner law), where sensory perception is relative to stimulus change, allowing automatic filtering of static elements to prevent overload (Fechner, 1960). Focus scoping draws from attentional theories, prioritizing foveal (central) over peripheral vision to manage information (Orienting of Attention, 1980). We theorize that emulating these processes in SSDs can resolve sensory overload and fatigue by delivering intuitive, context-aware feedback, unlike raw data in traditional devices.

Additionally, modularity is based on user-centered design theory, positing that customizable systems better accommodate diverse impairments and preferences (Norman, 2013). By integrating IoT for generalized situations (e.g., API-driven apps), the framework hypothesizes improved adoption, solving lab-to-real-world gaps through adaptive, brain-like processing.



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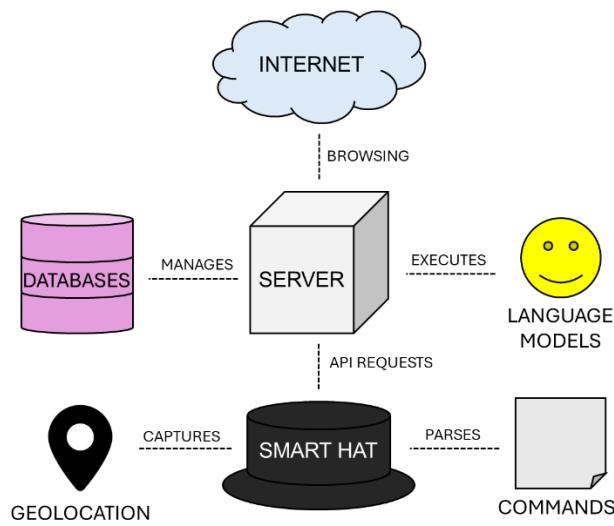


Figure 2: IoT System Architecture of the whole system

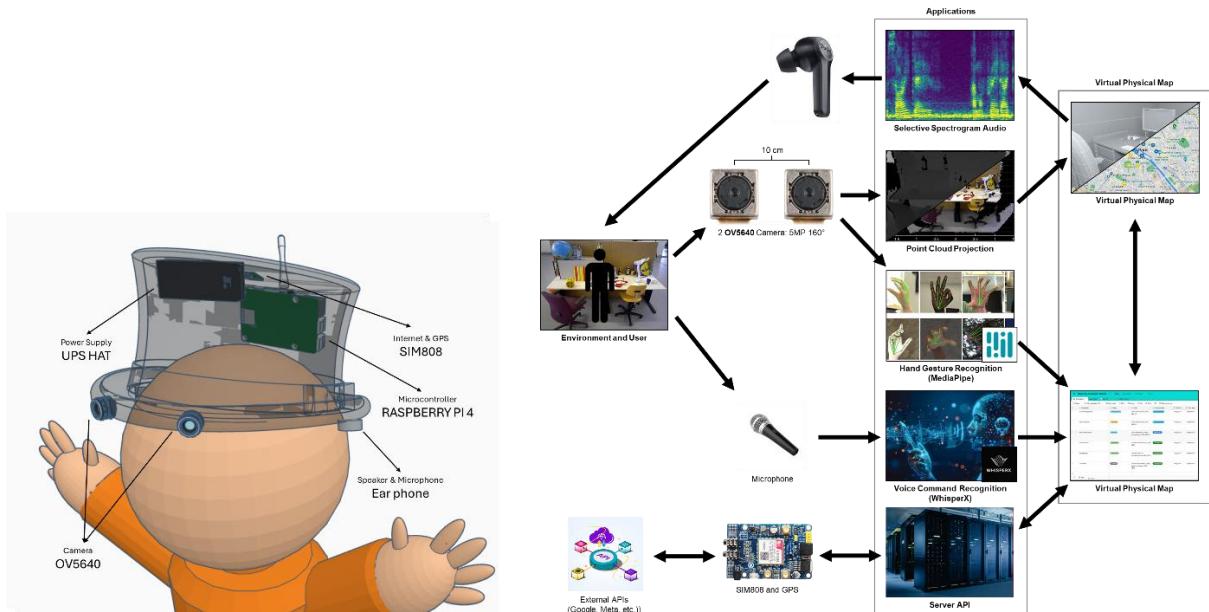


Figure 3: Basic Architecture of an Embedded System



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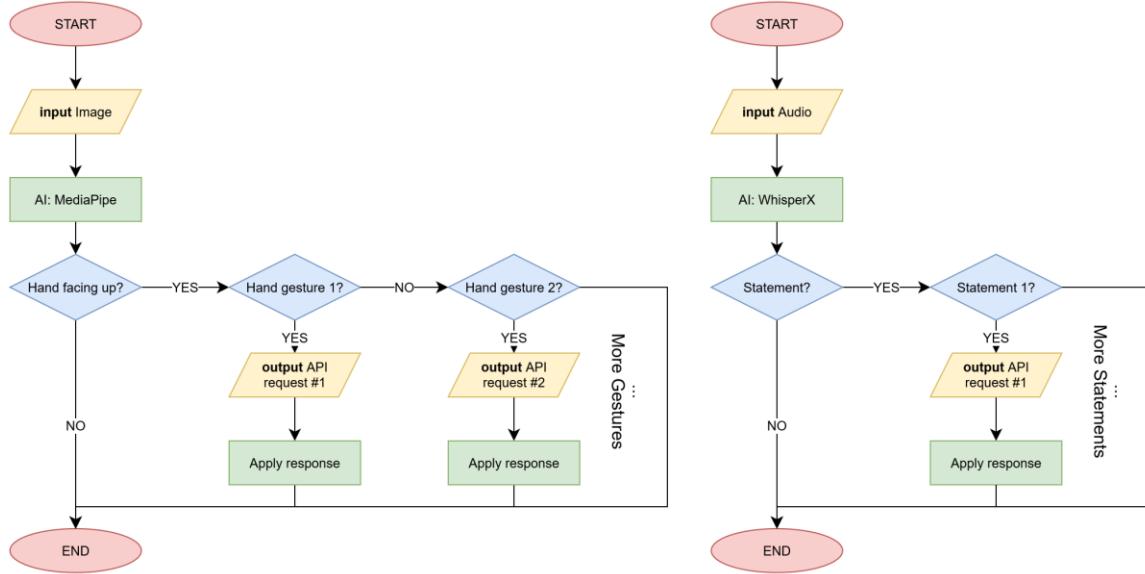


Figure 4: Flowchart of the AI in the System

Scope and Delimitations

Our device should work both indoors and outdoors to minimize inconvenience. To prevent scope creep, we focus primarily on sensory substitution via virtual worlds for visual-to-audio translation, ensuring interpretability. Secondarily, we emphasize modularity for user-specific processes and tracking physical/digital environments. Delimitations include potential power and weight issues as a wearable prototype, excluding non-essential features like advanced AI beyond basic recognition.

Related Studies

Several studies inform our work:

- **AuralVision** (AuralVision, n.d.): Converts depth via ToF lasers to stereo sound; provides depth encoding insights but lacks modularity.



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- **Eyesynth's NIIRA** (Eyesynth NIRRA, 2021): Uses RealSense D415 for spatial audio; highlights semantic integration, aiding our point cloud approach.
- **Unfolding Space Glove** (Jakob Kilian, 2022): Haptic feedback for hand-object distance; informs ergonomics but is hand-specific.
- **Virtual Whiskers** (Junchi Feng, 2024): AI-driven vibration for paths; supports obstacle density mapping in our virtual world.
- **Depth Sonification** (Louis Commère, 2023): LiDAR-to-repetition rate; guides our spectrogram design for depth.
- **SoundSight App** (Giles Hamilton-Fletcher, 2021): Mobile color/depth to audio; inspires multi-feature translation.
- **Smart Hat** (Memoona Sami, 2024): Object detection to voice; aids IoT integration.
- **Clearway Companion** (Akshay Vijay Panchal, 2024): Haptic/audio with motion; informs user feedback.
- **Multi-faceted SSD** (Ligao Ruan, 2025): Audio-based curb detection; enhances real-time alerts in our system.
- **Multi-path Navigation** (Zaidao Han, 2025): Low-vision mobility; supports virtual pathfinding.
- **BrainPort Vision Pro** (Yiming Zhao, 2025): Functional evaluation; guides our testing protocols.
- **Smart Vision Glasses** (Devi Udayakumar, 2025): AI-powered glasses; informs gesture/voice interfaces.



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AuralVision uses ToF lasers for depth-to-stereo sound via bone conduction, achieving lab-based navigation but limited by sensor range (AuralVision, n.d.). Eyesynth's NIIRA integrates RealSense cameras for semantic audio, outperforming in object recognition but causing overload without human emulation (Eyesynth NIRRA, 2021). Unfolding Space Glove employs haptic motors for distance feedback, effective for grasping but non-wearable for head-based navigation (Jakob Kilian, 2022). Virtual Whiskers uses cameras/AI for vibration belts, reducing collisions by 30% in tests but lacking digital integration (Junchi Feng, 2024). Depth Sonification recommends repetition rates for depth, improving intuitiveness over raw tones (Louis Commère, 2023). SoundSight translates LiDAR/thermal to timbre/volume, enabling color/depth perception on mobiles but app-limited (Giles Hamilton-Fletcher, 2021). Smart Hat detects objects via camera for voice output, cost-effective but non-modular (Memoona Sami, 2024). Clearway uses PIR sensors for haptic alerts, user-friendly but sensor-constrained (Akshay Vijay Panchal, 2024). Newer studies like multi-faceted SSDs show 85% accuracy in curb detection, aligning with our audio focus (Ligao Ruan, 2025). Our work builds on these by adding brain emulation and IoT for superior overload reduction and versatility

Review Literature

Sensory Substitution and Assistive Technology

The pervasive integration of computing in society has ushered in novel possibilities for human-world interaction, exemplified by smartphones and affordable wearables that provide access to an ever-expanding data network (Real & Araújo, 2023). This technological proliferation has particularly benefited the field of assistive technology,



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enabling the development of sophisticated tools that enhance the independence and quality of life for individuals with visual impairments (Muhsin et al., 2023). These innovations frequently leverage multi-sensor data fusion to offer comprehensive environmental understanding, crucial for navigation and obstacle detection (Theodorou et al., 2023). For instance, current research explores how object detection algorithms, combined with accessible interfaces, can allow visually impaired individuals to perceive and navigate their surroundings with greater autonomy (Ikram et al., 2024). The development of such devices is crucial given the over 2.2 billion people globally affected by visual impairment, significantly restricting their independent mobility and overall access to their environments (Chandra et al., 2025). This challenge is further compounded by the projected increase in visually impaired individuals, reaching 61 million blind and 474 million with moderate to severe vision impairments by 2050, underscoring the urgent need for advanced assistive solutions (Xu et al., 2023). These advanced solutions often integrate diverse sensor modalities and employ deep learning to interpret complex spatial data, effectively translating visual information into alternative sensory cues (Theodorou et al., 2023). For example, smart stick devices incorporate ultrasonic sensors and camera modules to detect and identify obstacles, providing feedback through audio messages and haptic vibrations to guide users (Farooq et al., 2022). Some systems also incorporate moisture and soil sensors for detecting puddles and uneven terrain, further enhancing navigational safety and environmental awareness for visually impaired individuals (Ikram et al., 2024) (Okolo et al., 2025) (Farooq et al., 2022). Furthermore, recent advancements in assistive technology emphasize the use of multimodal feedback mechanisms, integrating haptic, auditory, and even olfactory cues to provide a rich, interpretable representation of the environment



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(Muhsin et al., 2023). Despite these technological advancements, the user acceptance of many developed solutions remains relatively low, primarily due to insufficient involvement of visually impaired individuals in the design, development, and evaluation phases, leading to challenges in human factors and user experience (Muhsin et al., 2023). Addressing these limitations necessitates a paradigm shift towards co-creative design methodologies that prioritize the lived experiences and unique navigational challenges faced by visually impaired individuals, ensuring solutions are both technologically sophisticated and practically usable (Manzoor et al., 2022). This user-centric approach is vital for developing effective assistive technologies, moving beyond mere functional efficacy to encompass usability, comfort, and psychological acceptance within real-world environments (Muhsin et al., 2023). Moreover, the integration of artificial intelligence and machine learning within these assistive technologies holds promise for further enhancing navigation, object recognition, and even predictive assistance, adapting to individual user patterns and environmental changes (Martinello et al., 2023).

Sensory substitution devices for the visually impaired to enhance environmental perception.

Many early assistive devices primarily focused on addressing technical problems for totally blind individuals, with less emphasis on the nuanced needs of those with partial vision or the critical human factors of usability and learnability (Muhsin et al., 2023). A significant limitation identified in the literature is the infrequent involvement of visually impaired individuals in the design and testing phases, with only 35.2% of developed aids being evaluated by the target users themselves (Muhsin et al., 2023). This lack of user



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involvement often results in technologies that, despite technical sophistication, fail to meet the actual needs and preferences of their intended users, contributing to low adoption rates and limited real-world impact (Soltani et al., 2025) (Muhsin et al., 2023). Consequently, the efficacy of assistive technologies for visual impairment is fundamentally contingent upon a robust user-centered design approach that systematically integrates feedback from diverse visually impaired populations, including those with partial vision and comorbidities like diabetes, from initial conceptualization through iterative refinement (Muhsin et al., 2023) (Ortiz-Escobar et al., 2023). This approach is critical for ensuring that assistive tools are not only technologically advanced but also intuitively usable, accessible, and genuinely beneficial in diverse real-world scenarios (Ortiz-Escobar et al., 2023). Furthermore, recent research highlights the potential of AI-powered assistive technologies, including smart glasses and smartphone applications, to support independent travel and enhance access to information by leveraging computer vision and natural language processing (Naayini et al., 2025) (Muhsin et al., 2023). These systems facilitate complex interactions in various contexts, effectively extending user cognition by distributing visual information processing (Xie et al., 2024). Despite these advancements, a notable gap remains in assistive technology research concerning individuals with Cerebral Visual Impairment, a leading cause of vision impairment that uniquely affects higher-order visual processing and is often overlooked in mainstream assistive technology development (Gamage et al., 2025) (Arora et al., 2024). This oversight underscores the need for more inclusive research paradigms that address the diverse spectrum of visual impairments, moving beyond a singular focus on ocular conditions to encompass neurological and cortical visual challenges (Muhsin et al., 2023). This includes integrating user-centered



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design methodologies from inception, ensuring that the development process is informed by the lived experiences of individuals with various visual impairments, including those with CVI, and not solely by technological capabilities (Martiniello et al., 2023). Meaningful inclusion of blind and low vision users, along with specialists in assistive technology and vision rehabilitation, from the initial stages of design is crucial for developing effective navigation-based applications (Martiniello et al., 2023). This collaborative approach ensures that the resulting tools not only address specific challenges but also integrate seamlessly with existing assistive strategies, such as dog guides or white canes, to provide comprehensive support during independent travel (Martiniello et al., 2023). Such co-design methodologies are instrumental in creating inclusive and equitable technologies that truly empower individuals with disabilities, enabling full participation in society and access to information (Pucci et al., 2024). Further research and development are needed to address technological and design issues, ensuring these assistive technologies are usable, efficient, and meaningful for all users (Sahoo & Choudhury, 2023).

Neuroscience of sensory substitution, specifically how the brain adapts to information presented through non-visual channels.

This neuroplastic adaptation allows individuals with visual impairments to develop compensatory strategies, utilizing other sensory modalities to process environmental information that would typically be perceived visually (Bennett et al., 2019). This process involves the brain reallocating cortical resources originally designated for visual processing to enhance the capabilities of remaining senses, such as touch and hearing, thereby enabling sophisticated spatial awareness and object recognition (Due & Lange,



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2016). This re-organization highlights the brain's remarkable capacity for plasticity, demonstrating how non-visual sensory input can drive the development of novel neural pathways for navigation and interaction with the environment (Bennett et al., 2019). Specifically, studies on auditory and tactile frequency mapping demonstrate how such sensory substitution can convey visual distance perception, leveraging the brain's cross-modal processing capabilities (Jiang et al., 2025). Furthermore, sensory substitution techniques, while showing promising results in laboratory settings, have not yet achieved widespread adoption in real-world applications, underscoring the need for further research into user-centric design and integration with existing mobility aids (Lloyd-Esenkaya et al., 2020) (Soltani et al., 2025). Future research should therefore focus on better studying these processes; an endeavor that can be facilitated by the recent advances in audio-based virtual reality (Bleau et al., 2022). These developments in virtual reality allow for controlled experimental environments to better understand the neural mechanisms underlying sensory substitution and to refine devices for practical adoption (Maidenbaum, 2015).

Assistive technology for blind individuals, including electronic navigation aids and their effectiveness in real-world environments.

A critical aspect of this research involves assessing how sensory substitution devices leverage brain plasticity to facilitate environmental perception, often by engaging cortical areas typically associated with visual processing (Ueda et al., 2019). This adaptation allows for the interpretation of complex spatial and perceptual information through alternative sensory channels, like audition or touch, thereby expanding the



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functional capabilities of individuals with visual impairments (Netzer et al., 2021). This neuroplasticity has been observed where visual cortices are recruited in blind individuals utilizing sensory substitution devices, particularly for tasks involving spatial processing and navigation (Netzer et al., 2021) (Ueda et al., 2019). This suggests that artificial sensory inputs from substitution devices can be effective in controlling trunk movements during circumvention tasks, potentially by providing information about obstacle distance or trunk angular motion (Allum et al., 2022). Despite these advancements, concerns remain regarding the discrepancies between real and virtual experiences in multisensory perception, partly due to the primary reliance on visual and auditory input without full integration of other modalities (Kang et al., 2024). Consequently, virtual reality platforms are emerging as invaluable tools for developing, testing, and refining such electronic travel aids, offering ecologically valid environments that bridge the gap between laboratory studies and real-world demands (Fialho et al., 2021) (Ricci et al., 2023). These platforms provide a broad spectrum of experiential contexts across various domains, enabling the development of more naturalistic studies of human behaviors while controlling for environmental variables (Kang et al., 2022). The integration of haptic feedback, specifically, can enhance these virtual environments by providing a more precise temporal resolution than vision or hearing, thereby enriching multisensory experiences within digitalized contexts (Kang et al., 2024). This increased precision allows for a more nuanced understanding of how haptic inputs modulate perceived plausibility and integration of sensory information within virtual environments, offering significant implications for rehabilitation therapies targeting sensorimotor functions (Kang et al., 2024). Moreover, these sophisticated virtual environments, coupled with advancements in multisensory



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integration, hold profound potential for the development of adaptive rehabilitation strategies that leverage neuroplasticity to restore visual function, particularly in conditions like hemianopia and retinal degeneration (Lucchesi et al., 2025). Electronic navigation aids often convert environmental information into stimuli for intact sensory organs, such as the vOICe system translating visual scenes into soundscapes or the EyeMusic device associating colors with musical instruments (Ueda et al., 2019). These systems demonstrate the feasibility of sensory substitution, converting visual data into alternative sensory formats to aid spatial awareness and object recognition for individuals with visual impairments (Negen et al., 2023). However, despite the functional gains, the perceptual experience for users of these devices often differs significantly from natural vision, necessitating further research into optimizing the mapping algorithms and user interfaces to reduce cognitive load and improve intuitive understanding (Tivadar et al., 2023). This optimization is crucial for moving beyond laboratory efficacy to widespread practical application, addressing the urgent need to standardize methodologies and deepen the understanding of mechanisms producing reliable transfer effects in real-world contexts (Culicetto et al., 2024).

Point Cloud Projection for Navigation

A notable advancement in this regard is the use of haptic feedback based on tactile and kinesthetic input, which can establish a tactile connection with the user, thereby enhancing the sense of “reality” in virtual environments (Muhsin et al., 2023). This integration is crucial for creating more immersive and effective virtual reality training interventions, particularly in rehabilitation, where improved depth perception and



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congruent sensory information can enhance movement quality and promote neuroplasticity (Wenk et al., 2022). Such multi-sensory feedback systems, including visual, auditory, and haptic elements, are particularly relevant for sensory substitution devices, enabling a richer and more intuitive representation of visual information through alternative modalities (Lerousseau et al., 2021). This convergence of advanced virtual environments and sophisticated multi-sensory feedback systems facilitates an enhanced understanding of spatial layouts, as demonstrated by studies where blind participants effectively distinguished intricate details of virtual environments after extensive training (Memeo et al., 2023). Furthermore, the digital rendering of tactile information and vibrotactile maps provides use-case flexibility, allowing for dynamic, multimodal, and portable platforms that can incorporate vibration, audio, and kinesthetic feedback to convey dense and complex spatial information, thereby enhancing learning outcomes (Tivadar et al., 2023). For instance, recent research highlights the superiority of skin-stretch cues over vibrotactile cues in conveying object location and movement to visually impaired users in virtual reality, indicating a promising direction for enhanced haptic feedback design (Li et al., 2025). Digital haptics, particularly those employing ultrasounds, represent a significant alternative learning tool for complex spatial scenes and navigation in unfamiliar layouts, holding promise for the rehabilitation of spatial functions and the mitigation of visual impairments (Tivadar et al., 2023). Moreover, this approach can enhance motor rehabilitation by integrating cutaneous signals from contact points with objects and proprioceptive signals about mechanoreceptor configuration to improve the perception of object shape and texture (Tivadar et al., 2023). These multimodal haptic systems, integrating various sensory inputs beyond vision and hearing, can significantly improve



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the accuracy of virtual limb use, mediate tactile information from robots to users, and restore a sense of touch to prosthetic hands, thereby supporting augmented action in a way that replicates real-life human sensory modalities (Raisamo et al., 2019).

Point cloud data and its application in environmental modeling .

This involves creating detailed 3D representations of environments by projecting point cloud data onto navigable surfaces, thereby allowing for sophisticated spatial analysis and interaction within virtual or augmented realities (Memeo et al., 2021). This technique is crucial for developing highly realistic and interactive virtual environments, enabling users to perceive and manipulate virtual objects with greater fidelity and immersion, particularly through enhanced tactile and proprioceptive feedback (Kim et al., 2021). Furthermore, the integration of haptic feedback within such environments has demonstrated superior qualities in intuitiveness, accuracy, and immersion compared to traditional 3D visualizations, highlighting its transformative potential in boosting sensory engagement with data (Masud et al., 2023). This is particularly evident in mixed reality applications, where realistic haptic feedback mitigates the common issue of a disconnect between visual and tactile perceptions, thereby enriching the immersive experience (Wang, 2024). This innovation allows for the transformation of everyday physical objects into adaptive haptic interfaces for AI-generated virtual assets, bridging the gap between the digital and physical realms (Wang, 2024). Such advancements are vital for enhancing context awareness and facilitating more intuitive human-computer interaction, especially when considering the integration of AI-driven multimodal interfaces (Hu et al., 2024). Moreover, this approach can leverage large language models to interpret and materialize



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user intentions, enhancing the creative potential of such systems by incorporating estimated tactile sensations of real objects as part of the input (Wang, 2024). This multifaceted approach creates a novel framework for intelligent environments that are not only responsive but also proactively enhance human perception and interaction within mixed realities (Yamaguchi et al., 2024). This is particularly pertinent in intelligent environments that aim to understand and respond to human needs and behaviors through interconnected sensor networks, enhancing overall quality of life and work efficiency (Yamaguchi et al., 2024). The proliferation of consumer-level head-mounted displays underscores the increasing feasibility of blurring the lines between real and virtual, yet haptic feedback remains a critical, often absent, element in current mixed reality experiences (Wang, 2024). This gap highlights the necessity for advanced haptic technologies that can dynamically transform any physical object into a versatile haptic prop, enabling a more coherent and immersive virtual experience (Wang, 2024). This capability would necessitate advanced techniques for accurately identifying and processing multiple items, representing a significant leap forward with new possibilities for personal entertainment and creative workflows (Wang, 2024). This would allow for more sophisticated interactions where virtual objects can be manipulated with real-world tactile sensations, further blurring the line between physical and digital realities (Joolie & Uddin, 2024). This integration is critical for developing sophisticated mixed reality systems that offer believable environmental manipulations, allowing users to interact with virtual content as if it were physically present (Kari et al., 2023). The complex development process inherent in Mixed Reality experiences provides fertile ground for the application of Artificial Intelligence tools across all stages, especially within the creative sector (Dima & Daylamani-Zad,



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2024). This can significantly enhance user engagement and creativity, opening up unprecedented ways to interact with products and content in various fields like health, fashion, and art (Alessandrini & Rognoli, 2023). This approach could provide consumers with a more holistic sensory engagement, allowing for multi-dimensional immersion that assimilates all senses, thereby transforming fields such as culinary arts or perfumery (Yin et al., 2023). These advancements highlight the economic potential of mixed reality applications, which are evolving from purely ludic interactions to professional applications that enhance the realism and sense of presence in virtual experiences (Imbesi et al., 2023).

Use of 3D point cloud data in robotics and autonomous navigation to help with the precise location of objects in real-time.

This capability is further augmented by recent advancements in neural rendering and 3D scanning on personal devices, coupled with AI integration, which democratizes the production of virtual materials and objects, enabling non-skilled users to create content more intuitively (Imbesi et al., 2023). This convergence allows for the processing of low-quality point cloud data without complex AI, reinforcing the potential for accessible and efficient 3D content generation (González et al., 2023). This ease of creation, combined with advanced techniques such as active contour models for real-time object tracking, facilitates the seamless integration of real-world objects into mixed reality environments, enhancing interactive experiences (Wang, 2024). Furthermore, the evolution of mixed reality technology, propelled by innovations in artificial intelligence and wearable devices, extends its applicability beyond entertainment to critical sectors such as medicine and industrial operations, enabling higher fidelity visualization and dynamic registration



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methods (Bonsmann et al., 2024). This expanded scope underscores the increasing demand for advanced 3D vision systems that integrate multiple data modalities like text, images, and point clouds for robust object recognition and scene understanding in complex environments (Wang et al., 2024). Such multimodal integration significantly enhances feature representation, particularly in scenarios involving sparse, noisy, or corrupted point cloud data, thereby improving detection accuracy (Agha et al., 2024). This enables more accurate, safe, and rapid interaction with interventions through AI-enabled overlays and auto-segmentation, expanding the range of applications in medical settings (Bonsmann et al., 2024). Moreover, the use of point cloud data allows for rapid object recognition and 3D pose estimation, which is crucial for dynamic environments where real-time interaction is paramount (Lee et al., 2021). This includes leveraging dense point clouds, which represent a collection of sparsely sampled points from continuous surfaces, to construct comprehensive 3D semantic models for autonomous robotic vehicles (Vishnyakov et al., 2021) (Tohidi et al., 2024). These advancements in 3D scene understanding, coupled with generative AI capabilities, enable the creation of highly immersive mixed reality experiences by seamlessly integrating AI-generated virtual objects into real-world environments (Wang, 2024). This paradigm shift simplifies the development pipeline, allowing for more efficient and less cumbersome creation of digital twins and interactive 3D models (Ratican et al., 2023) (Zhao & Larsen, 2024). The nascent field of automatic 3D content generation continues to face challenges, including data scarcity and computational resource limitations, despite significant advancements in text and image generation (Zhao & Larsen, 2024).



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Previous work on point cloud visualization technologies and haptic feedback systems

for improving spatial awareness in visually impaired individuals.

These technologies hold promise for enhancing navigation and interaction with complex environments, providing a richer understanding of spatial relationships through non-visual cues (Zha et al., 2025). Furthermore, integrating 3D scene understanding with textual descriptions allows for a deeper interpretation of the environment, enabling sophisticated embodied AI applications that can navigate and interact based on natural language commands (Zhu et al., 2024) (Liu et al., 2024). However, the computational demands of integrating massive 3D point clouds with semantic data in real-time within a Web-AR framework remain a significant challenge (Kharroubi et al., 2020). This limitation underscores the need for optimized data structures and processing algorithms, such as hierarchical Octree structures, to enable efficient real-time interaction and manipulation of large datasets on mobile devices (Kharroubi et al., 2020).

IoT Sensors in Assistive Devices

Such sensors provide real-time environmental data, which, when combined with AI-driven point cloud analysis, can offer enhanced navigational aids and object recognition for individuals with visual impairments. This synergy enables the development of sophisticated assistive technologies that leverage both pervasive sensing and advanced 3D spatial understanding to create more accurate and responsive guidance systems (Kharroubi et al., 2020). The integration of advanced 3D scene understanding with generative AI could further enable the creation of interactive, AI-generated 3D environments, addressing current limitations where generated scenes remain static (Qian, 2024).



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Research on IoT sensors and their integration with assistive technologies, including their role in providing real-time environmental data for blind users.

This approach can leverage multimodal large language models that process live video feeds to interpret and interact with the real world, offering new capabilities for individuals with visual impairments (Chang et al., 2025) (Ainary, 2025). However, current AI systems often struggle with dynamic situations, providing inadequate live descriptions and exhibiting inaccuracies in spatial and distance information, which can lead to confusion and distrust among users (Chang et al., 2025). This highlights a critical need for more robust AI algorithms capable of real-time, context-aware processing to ensure reliable and trustworthy assistance for visually impaired individuals (Xie et al., 2024). The current reliance on AI-powered assistive tools, while beneficial, necessitates further investigation into their practical utility and limitations within real-world scenarios for visually impaired users (Xie et al., 2024) (Xie et al., 2025). Addressing these challenges requires a concerted effort to enhance AI model accuracy, particularly in recognizing diverse obstacles and providing detailed feedback, a gap that previous iterations of assistive technologies, such as white canes and early ultrasound-based devices, could not adequately fill (Chandra et al., 2025). A recent study revealed that despite advancements in assistive devices and smartphone applications, user acceptance remains low, primarily due to insufficient visually impaired participant involvement during conception, building, and testing phases (Muhsin et al., 2023). Consequently, it is imperative to adopt a user-centered design approach, ensuring that visually impaired individuals are active participants throughout the entire development lifecycle of new assistive technologies to ensure their practical efficacy and broader adoption (Xie et al., 2025) (Karamolegkou et al., 2025). Moreover, expanding



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research efforts to include additional sensing capabilities, such as depth cameras, can provide more comprehensive environmental data, thereby enhancing the accuracy and utility of AI agents for real-world applications for individuals with visual impairments (Muhsin et al., 2023) (Chang et al., 2025). This integration offers a pathway towards creating a generalized vision-to-audio or vision-to-touch translator, yet still demands significant multidisciplinary research and improved algorithms for reliable everyday use (Muhsin et al., 2023). This collaborative approach is essential to overcome limitations such as the underrepresentation of individuals with disabilities in training datasets, which often leads to models performing poorly in real-world scenarios (Sahoo & Choudhury, 2023). Furthermore, the absence of sufficient representation for individuals with visual impairments in training datasets often results in models that exhibit low sensitivity or specificity, leading to unreliable performance in practical assistive technology applications (Sheng et al., 2024). This underscores the critical need for a more inclusive and representative dataset generation process to improve the efficacy and trustworthiness of AI-driven assistive technologies for visually impaired individuals (Muhsin et al., 2023). Therefore, involving visually impaired individuals, including rehabilitation professionals, directly in the design and development processes is paramount to creating truly effective and user-friendly assistive solutions (Martiniello et al., 2023) (Muhsin et al., 2023). This iterative co-design methodology, involving end-users and a multidisciplinary team, is crucial for identifying genuine user needs and preferences, thereby yielding more robust and representative assistive technologies (Ortiz-Escobar et al., 2023). Such an approach, centered on user experience and iterative feedback, not only addresses the specific challenges faced by visually impaired individuals but also fosters the development of

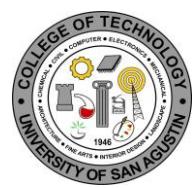


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adaptable and acceptable aids by integrating computer vision sensors and advanced algorithms directly informed by lived experiences (Muhsin et al., 2023). This ensures that the developed technologies are not only technologically advanced but also genuinely meet the diverse requirements of the visually impaired community, fostering greater autonomy and independence (Sahoo & Choudhury, 2023). This requires comprehensive capacity building in user-centered design principles across development teams and strategic planning for UCD implementation (Ortiz-Escobar et al., 2023). This capacity building extends beyond technical expertise to include an understanding of the social and psychological aspects of visual impairment, thereby fostering the creation of assistive tools that are both functionally superior and ethically sound (Martiniello et al., 2023).

The use of wearable IoT devices (such as smart glasses, smart hats, or vests) for real-time navigation and obstacle detection.

Such devices, often integrated with mobile applications, preprocess sensor data to provide directional guidance and enhance user security in dynamic environments (Ikram et al., 2024). This can significantly improve the independence and mobility of individuals with visual impairments by addressing common navigational challenges (Soltani et al., 2025). Despite their potential, these systems must incorporate robust feedback mechanisms and involve end-users throughout their design to ensure practical utility and widespread



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adoption (Martiniello et al., 2023) (Ortiz-Escobar et al., 2023). Wearable IoT devices are increasingly seen as a promising solution for augmenting the capabilities of traditional assistive tools, offering advanced spatial awareness and personalized guidance (Messaoudi et al., 2022). However, the effective integration of these devices necessitates rigorous testing and validation in diverse real-world settings to ensure their reliability and accessibility for all visually impaired users (Martiniello et al., 2023). Moreover, considerations regarding cost-effectiveness and low-power consumption are vital for the widespread adoption of such advanced technologies, especially in developing regions (Muhsin et al., 2023). Further research should focus on optimizing battery life and exploring cost-effective manufacturing techniques to make these devices more accessible to a broader population, including those in low-resource settings (Muhsin et al., 2023).

Wearable IoT devices (such as smart glasses, smart hats, or vests) for real-time navigation and obstacle detection These systems typically leverage an array of sensors, including cameras and ultrasonic detectors, to gather environmental data, which is then processed by embedded microcontrollers or cloud-based AI algorithms to generate actionable feedback for the user (Farooq et al., 2022). This feedback can take various forms, such as haptic vibrations, auditory cues, or even synthesized speech, all designed to convey critical information about the user's immediate surroundings and potential hazards (Farooq et al., 2022). Smart glasses that incorporate object detection algorithms can provide real-time audio descriptions of objects and obstacles, enabling a more intuitive understanding of the environment for visually impaired individuals (Ikram et al., 2024). Conversely, haptic feedback systems integrated into canes or wristbands can provide tactile cues, alerting users to changes in terrain or proximity to obstacles (Soltani et al., 2025). Similarly, advanced



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smart canes and wearable devices now incorporate cloud computing and artificial intelligence, offering sophisticated indoor navigation capabilities and object identification to guide users effectively through complex environments (Bouteraa, 2021). However, the efficacy of these technologies is often contingent on factors like the quality of the smartphone camera and consistent internet connectivity for remote image processing, posing potential limitations in varied environments (Muhsin et al., 2023). IoT smart hat systems address some of these limitations by integrating lightweight, low-power sensors and on-device processing to provide localized intelligence without constant reliance on external infrastructure (Farooq et al., 2022). This approach minimizes latency and enhances system reliability, making such devices particularly suitable for dynamic outdoor environments or areas with limited network access. These systems often incorporate machine learning algorithms to interpret sensor data, enabling accurate object detection, recognition, and pathfinding, which significantly enhances user safety and mobility in various real-world scenarios (Ikram et al., 2024). For example, some smart stick designs utilize ultrasonic sensors for obstacle detection, water sensors for puddles, and high-definition cameras for object recognition, providing multimodal feedback via vibrations and voice prompts to the user (Farooq et al., 2022). Such integrated solutions can detect nuanced environmental features, including varied terrains and dynamic obstacles, which traditional white canes might miss (Okolo et al., 2025) (Farooq et al., 2022). Furthermore, the integration of GPS/GSM modules in these smart sticks facilitates location sharing and emergency alerts, greatly augmenting the safety net for visually impaired individuals navigating unfamiliar or hazardous environments (Farooq et al., 2022). Another Wearable Device is a wearable IoT vest for the visually impaired, which integrates a camera and



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ultrasonic sensors to provide comprehensive obstacle detection and navigation assistance through haptic feedback (Muhsin et al., 2023). This vest design offers an intuitive interface by translating spatial information into tactile sensations, allowing users to perceive their surroundings without auditory overload. However, the current iteration of these vests often faces challenges related to sensor fusion accuracy and the computational demands of real-time image processing, necessitating further optimization to ensure reliable performance across diverse environmental conditions (Oladele et al., 2021).

Investigations on sensor fusion (e.g., combining ultrasonic, infrared, and vision sensors) to improve the accuracy of navigation systems for the blind.

This involves combining data from multiple sensors, such as ultrasonic, infrared, and cameras, to create a more robust and comprehensive understanding of the environment (Bala et al., 2023) (Farooq et al., 2022). This multidisciplinary approach, integrating knowledge from computer vision, machine learning, and domain-specific insights, is crucial for addressing the complex challenges of obstacle detection and warning systems (Ikram et al., 2024). Researchers have explored various methodologies for integrating sensor data, ranging from traditional Kalman filters to more advanced deep learning techniques, to enhance the precision and reliability of environmental perception for visually impaired individuals (Theodorou et al., 2023). Despite these advancements, a significant gap remains in thoroughly comparing multi-sensor data fusion techniques used in academic research with those implemented in commercial assistive technologies (Theodorou et al., 2023). For instance, some novel smart guiding devices integrate both depth and ultrasonic sensors to address the complex challenges of detecting transparent



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and small obstacles, a capability often limited in basic commercial products (Bai et al., 2017) (Muhsin et al., 2023). This fusion mitigates the limitations of individual sensors, as depth cameras can struggle with transparent objects, while ultrasonic sensors may lack the spatial resolution for intricate environments (Bai et al., 2017). Some systems, for example, process data from mobile Kinect sensors and integrate RealSense R200 cameras with RGB-D sensors to identify diverse obstacles like stairs, doors, chairs, sidewalks, and water hazards (Muhsin et al., 2023). These devices, which often employ algorithms derived from autonomous vehicle technology, aim for real-time performance and robustness across various environmental conditions, including previously unseen and dynamic settings (Toro et al., 2021). Furthermore, the integration of multiple sensor types and sophisticated fusion algorithms allows for a more holistic environmental representation, surpassing the capabilities of single-modality systems to provide enhanced safety and navigation for the visually impaired (Kolar et al., 2020) (Kovács & Nagy, 2020). In fact, studies have demonstrated that devices integrating multiple electronic sensors are effective at improving daily life for visually impaired individuals (Bai et al., 2017). However, a critical challenge remains in ensuring these sensor systems provide unambiguous feedback in noisy or complex environments, where misinterpretation of auditory cues can occur (Bai et al., 2017). This necessitates further research into adaptive feedback mechanisms, potentially incorporating haptic or multi-sensory feedback to convey environmental information more clearly and reduce cognitive load (Gao et al., 2025). Moreover, the integration of advanced machine learning models, particularly those trained on diverse datasets, can further refine the accuracy and adaptability of these multi-sensory systems to various environmental conditions and user needs (Ikram et al., 2024). Nevertheless, achieving a balance between



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computational complexity, power consumption, and real-time processing remains a persistent hurdle in deploying these advanced systems in practical, wearable assistive devices (Manzoor et al., 2022). There is also an investigation of combining ultrasonic, infrared, and vision sensors to overcome limitations inherent in individual sensors, enabling more robust obstacle detection and environmental mapping, though such fusion approaches introduce challenges in data synchronization and processing efficiency. One notable approach in this domain involves the use of 2D LiDAR and RGB-D cameras on smart canes, leveraging algorithms like Cartographer for simultaneous localization and mapping while identifying objects such as pedestrians and vehicles with improved YOLOv5 (Mai et al., 2024). While promising, these integrated systems still grapple with the precise detection and 3D representation of small or ground-level objects, an area requiring significant refinement (Oladele et al., 2021). Further, the adaptability of these systems to dynamic environmental conditions and their ability to differentiate between various obstacle types, such as static objects versus moving entities, requires more sophisticated algorithmic development (Warule et al., 2024). Even with advancements in sensor fusion, some existing prototypes for obstacle identification have been limited in scope, covering only small areas or failing to detect moving obstacles, and have often lacked thorough evaluation with visually impaired users (Muhsin et al., 2023). This highlights a critical need for more extensive testing with target populations and in diverse real-world scenarios to ensure the practical utility and reliability of these advanced assistive technologies before widespread adoption (Oladele et al., 2021). Future research should therefore focus on developing robust, real-time object detection devices utilizing optimized YOLO models, as highlighted by recent investigations, to assist visually impaired



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individuals in navigating complex outdoor environments safely and independently (He & Saha, 2023). This includes exploring efficient architectures like Tiny-YOLOv3, which can operate effectively on wearable devices while maintaining high accuracy for pedestrian detection (Maya-Martínez et al., 2023). Such models, when integrated with multi-modal sensor data, can significantly improve obstacle detection systems by making them more reliable and accurate for real-time applications (Ikram et al., 2024). Additionally, the development of larger, more diverse datasets encompassing a wide array of environmental conditions, object types, and scenarios is crucial for enhancing the robustness and generalization capabilities of these models in real-world settings (Ikram et al., 2024).

Haptic Feedback and Tactile Interfaces

Haptic feedback and tactile interfaces represent a crucial area for development, as they offer an alternative or complementary mode of information delivery to auditory and visual cues, which can be particularly beneficial in situations where sensory overload or environmental noise is an issue (Angelopoulos et al., 2019). These interfaces can convey detailed spatial and environmental information through vibrations, pressure, or temperature changes, allowing visually impaired users to perceive obstacles and navigate complex environments more intuitively and discreetly (He & Saha, 2023). For instance, vibrational patterns embedded in smart canes or wearables can effectively communicate the presence, distance, and even the nature of obstacles, thereby reducing reliance on auditory cues that can sometimes be ambiguous or intrusive (Martiniello et al., 2023). This tactile feedback can be particularly effective in noisy urban environments where auditory cues might be masked, or in situations demanding silent operation, offering a more private and integrated



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user experience. Further research is needed to refine the mapping of complex environmental data to intuitive haptic cues, ensuring that the information conveyed is both comprehensive and easily interpretable without imposing excessive cognitive load on the user. Moreover, integrating haptics with cross-modal learning approaches could further enhance the ability of visually impaired individuals to interpret complex sensory information, leading to improved spatial awareness and navigation capabilities (Muhsin et al., 2023) (Gao et al., 2025). For example, detailed haptic feedback can communicate not only the presence of an object but also its texture or shape, improving spatial cognition by leveraging the intricate relationship between sensation and spatial knowledge acquisition (Tivadar et al., 2023). This multi-modal approach, combining haptic with auditory and visual information (for sighted individuals), has been shown to improve learning and navigation through complex spatial layouts (Tivadar et al., 2023) (Dudley et al., 2023). Furthermore, virtual environments that integrate current Orientation and Mobility protocols can provide flexible and adaptable training strategies for haptic interpretation, allowing for a more nuanced understanding of spatial information (Memeo et al., 2023). The integration of multimodal systems, which combine various input and output modalities, can further enhance accessibility and user interaction for individuals with visual impairments (Muhsin et al., 2023). Specifically, haptic feedback through vibrotactile patterns can significantly enhance spatial guidance and information conveyance in virtual reality environments, improving locomotion for blind and visually impaired users (Anderton et al., 2024). This approach leverages the inherent accessibility of haptic feedback, which does not require extensive training for users to interpret, and aligns with the growing industry focus on advanced haptic technologies in handheld controllers.



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(Anderton et al., 2024). The development of vibrotactile patterns for non-visual information presentation holds significant promise for aiding blind and visually impaired individuals in navigating their surroundings effectively (Khusro et al., 2022). Moreover, these haptic feedback mechanisms can be enhanced through advanced computational models that translate complex environmental data into easily discernible vibrotactile sensations, thereby increasing the precision and utility of tactile interfaces for diverse navigational tasks (Joolee & Uddin, 2024). Such advanced systems often incorporate multi-modal approaches, combining haptic feedback with auditory and visual cues to deepen understanding and improve cognitive levels for visually impaired individuals (Zhu & Yang, 2023).

Studies on haptic feedback technology for navigation, including wearable devices that convert data into tactile sensations.

For example, research has demonstrated that skin-stretch cues are more effective than vibrotactile cues in conveying the spatial location and movement of virtual objects to blind users (Li et al., 2025). However, the development of sophisticated vibrotactile patterns remains critical for non-visual information presentation, particularly in applications like digital graphic exploration where continuous vibrations have proven insufficient (Zhao et al., 2020). To overcome this limitation, novel approaches focusing on variations in vibration intensity and frequency, or combinations thereof, are being explored to encode richer and more nuanced information about the environment, which is crucial for supporting the spatial performance of visually impaired individuals (Anderton et al., 2024) (Jiang et al., 2025). For instance, microelectromechanical devices and advanced haptic



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training approaches are generating renewed interest in using touch as a communication channel to supplement or replace visual and auditory modalities that may be overloaded or absent (Nyasulu et al., 2021). This includes leveraging haptic feedback in mobile applications to enhance accessibility for visually impaired individuals, ensuring better social inclusion and autonomy (Paratore & Leporini, 2023). The efficacy of such systems is further bolstered by integrating advanced object detection and AI-driven reasoning, allowing for real-time tactile guidance and improved obstacle avoidance in complex environments (Tokmurziyev et al., 2025). Such integrated systems leverage the strengths of various technologies to provide comprehensive assistance, offering a pathway toward enhanced independence and improved quality of life for visually impaired users (Paratore & Leporini, 2023) (Muhsin et al., 2023). This includes exploring unconventional haptic exploration strategies, such as horizontal left-to-right and then vertical top-to-bottom navigation for shape recognition, which have been observed in blind users interacting with vibrotactile touchscreens (Sadia et al., 2021). These strategies highlight the importance of designing haptic interfaces that align with natural exploratory behaviors to optimize information transfer and user comprehension (Jiang et al., 2025). Furthermore, advancements in materials science and actuator technology are enabling the development of more sophisticated haptic feedback devices capable of rendering complex tactile sensations with greater fidelity, which is paramount for conveying detailed spatial information (Tivadar et al., 2023). Further research aims to adapt such apparatus for electrostimulation studies, expanding the scope of tactile perception research (Stein et al., 2023). These investigations are crucial for refining the design of tactile interfaces and



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ensuring that they are universally accessible and effective for individuals with diverse sensory needs (Stein et al., 2023).

Research on the integration of tactile feedback with auditory cues, allowing visually impaired users to navigate using both sensory modalities.

This multimodal approach, which also incorporates haptic feedback, can significantly enhance spatial understanding and interaction within digital environments, particularly for web browsing and map exploration (Giraud et al., 2017). Furthermore, recent advancements in digital haptics, utilizing ultrasonic feedback to dynamically alter perceived friction, offer promising avenues for conveying complex spatial layouts and object relations, even for those with visual impairments (Tivadar et al., 2023). This includes research into haptic contrast perception through electrovibration, which can be applied to both visually impaired and normally sighted individuals (Vardar et al., 2018). Additionally, the development of surface haptics is anticipated to extend beyond electronic device touch surfaces to encompass any flat, curved, or flexible physical surface with embedded computational capabilities (Başdoğan et al., 2020). This expansion facilitates the creation of interactive tactile maps and interfaces that can deliver nuanced spatial information, thereby augmenting navigational independence for visually impaired individuals (Yang et al., 2025). Such progress is vital for developing haptic interfaces that offer a more immersive and realistic user experience by integrating artificial tactile sensations with audiovisual technologies (Lim et al., 2024).



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Wearable Technology for the Visually Impaired

These devices often incorporate haptic feedback mechanisms, such as vibrating patterns, to convey navigation instructions and environmental information directly to the user, enhancing independent mobility in complex outdoor environments (Tachiquin et al., 2021) (Muhsin et al., 2023). These innovations can foster positive changes in attitudes and behavior toward individuals with visual impairments by raising awareness and understanding of their conditions, while also leading to the development of inclusive objects and environments (Reinhardt et al., 2019). Moreover, the continued refinement of these wearable technologies, including advancements in miniaturization and power efficiency, is poised to make them more ubiquitous and seamlessly integrated into daily life, offering sustained support for a broader range of activities. This is especially pertinent given the ongoing challenges in translating research prototypes into widely adopted production aids, which often stems from insufficient consideration of human factors and the nuanced distinctions between varying degrees of visual impairment (Muhsin et al., 2023). Some examples of the wearable urban mobility assistive devices for visually impaired pedestrians utilize smartphone capabilities for positioning and guidance, translating navigation instructions into vibrating patterns delivered via a foot-placed tactile interface (Tachiquin et al., 2021). These devices have shown promise in user experiments, where both sighted and visually impaired individuals successfully recognized the tactile feedback and found the system useful and easy to master for navigating urban pathways (Tachiquin et al., 2021). Nevertheless, these systems often face limitations in providing a sufficiently wide viewing range or adapting automatically to dynamic user speeds (Muhsin et al., 2023). Wearable glasses equipped with advanced sensors and augmented reality



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overlays are emerging as a sophisticated solution, offering real-time environmental data and navigational cues through multimodal feedback, including haptic vibrations and auditory signals. This integration of sensory inputs allows for a more comprehensive understanding of the surroundings, thereby significantly improving the safety and independence of visually impaired pedestrians when navigating complex urban environments (Ren et al., 2025). Despite these advancements, users frequently report a significant mental load when interacting with complex wayfinding systems, especially in noisy and dynamic urban settings (Parker et al., 2021). To mitigate this cognitive burden, researchers are exploring adaptive interfaces that dynamically adjust the level of information provided based on environmental complexity and user cognitive state, potentially incorporating biofeedback mechanisms to optimize information delivery. This includes the development of systems that can intelligently filter extraneous data, presenting only the most critical navigational cues in real-time to reduce cognitive overload and enhance user experience (Tachiquin et al., 2021). Another example is a cane that employs sensors to detect obstacles and provide haptic feedback, representing a classic approach to augmenting traditional mobility aids for enhanced safety and navigation (Martiniello et al., 2023). More recent advancements include smart sticks that utilize vibration and auditory feedback to alert users to both static and dynamic obstacles, although comprehensive testing with visually impaired individuals is not always explicitly detailed (Muhsin et al., 2023). Many devices emphasize multimodal feedback, recognizing that combining visual, auditory, and haptic cues can significantly improve user experience and decision-making efficiency, particularly in complex scenarios like street crossings (Ren et al., 2025) (Parker et al., 2021). ETA devices, for instance, often combine sound or synthetic voice with tactile



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feedback to guide users, although the effectiveness can depend on the user's ability to interpret these cues and integrate them with their own understanding of the environment (Bai et al., 2017). However, studies indicate that haptic stimuli can be less intuitive than audio feedback and may increase cognitive load and working memory when navigating with certain assistive devices (Lupu et al., 2020). This highlights a critical need for balanced multimodal feedback strategies that optimize information delivery without overwhelming the user's cognitive resources (Lupu et al., 2020). The integration of multiple features, such as haptic and auditory signals, shows promise in conveying more robust information, yet designers must carefully consider potential information overload when fusing different interfaces (Wang et al., 2020). To mitigate this, a user-centered design approach is essential, focusing on individualized preferences and adaptive interfaces that dynamically adjust the information density based on the user's cognitive state and environmental context (Muhsin et al., 2023). Moreover, the inclusion of personalized settings, allowing users to customize the speed and verbosity of wayfinding information, along with adjustable audio, visual, and haptic features, is crucial for improving accessibility and usability across diverse user needs (Parker et al., 2021) (Khusro et al., 2022) (Muhsin et al., 2023). For instance, systems combining haptic information delivered through belts with supplementary auditory cues, often via bone conduction earbuds, can enrich navigational support without occluding ambient environmental sounds, thus enabling a more comprehensive spatial awareness (Parker et al., 2021).



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Research on the development of wearable devices such as glasses, hats, or vests that use various sensory inputs (like sound or touch) to help blind individuals navigate.

This focus on diverse wearable form factors underscores a design philosophy that prioritizes hands-free operation and seamless integration with daily activities, aligning with user preferences for discrete and convenient assistive technologies (Parker et al., 2021).

Work on the development of smart hats and headgear with built-in sensors for location tracking and environmental mapping.

These devices often integrate with smartphone applications to provide multimodal feedback, such as auditory cues and haptic alerts, guiding users through complex indoor and outdoor environments (Ohn-Bar et al., 2018). This ongoing research also highlights the importance of user-centric design in developing navigation aids for individuals with visual impairments, ensuring that the technology addresses specific user needs, preferences, and the human factors of user experience, such as usability and learnability (Muhsin et al., 2023) (Soltani et al., 2025). Furthermore, investigations into personal needs within navigation interfaces extend beyond simple route preferences and feedback modalities, delving into the critical aspects of content selection and timing of instructions to minimize navigation errors (Ohn-Bar et al., 2018). This includes considering the optimal level of detail for instructions, varying based on the user's familiarity with an environment and their cognitive load at a given moment (Parker et al., 2021). One study on the Development of headgear with built-in sensors for location tracking and environmental mapping found that real-time adjustments to guidance based on dynamically updated environmental data significantly enhanced navigational accuracy and reduced user



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disorientation (Muhsin et al., 2023). Such personalized and adaptive navigation solutions are vital for enabling individuals with visual impairments to build mental maps of their surroundings and to navigate unfamiliar environments with greater confidence and independence (Soltani et al., 2025). Despite these advancements, a significant gap remains in comprehensively understanding how navigation systems integrate with existing assistive technologies and mobility aids, alongside the types of navigation systems available for visually impaired persons (Abidi et al., 2024).

Studies exploring the effectiveness of wearable navigation aids, including systems that combine environmental sensing, GPS, and real-time feedback.

There is a notable need for research that addresses the critical transitions between indoor and outdoor environments, and how public transit can be holistically integrated into route planning for individuals with visual impairments (Parker et al., 2021). Future research should delve into identifying the specific landmark, clue, and cue information essential for seamless transitions between diverse environments (Parker et al., 2021). Moreover, a comprehensive review of existing navigation methods, encompassing various feedback and localization techniques, reveals that current approaches often prioritize either indoor or outdoor environments, neglecting the dynamic interchange between them (Messaoudi et al., 2022). This oversight presents a significant barrier to independent mobility, as real-world navigation frequently necessitates movement across both settings, often involving public transportation networks that introduce additional complexities and environmental variations (Parker et al., 2021). Further, understanding the usability and effectiveness of navigation tools and methods for visually impaired persons requires detailed analysis of



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diverse strategies including speech and voice recognition, deep learning, and vision-based approaches (Messaoudi et al., 2022). Such analyses are critical for developing inclusive interface paradigms that leverage technological advancements while addressing the multifaceted navigation needs of the blind and low vision population (Martiniello et al., 2023). Additionally, the integration of artificial intelligence and computer vision in mainstream applications offers promising avenues for enhancing navigation through automated visual interpretation and real-time object recognition (Martiniello et al., 2023). This integration can facilitate more accurate obstacle detection and object identification, which are currently among the least reported categories of unmet needs in navigation applications for individuals with visual impairments (Martiniello et al., 2023). However, it is crucial that these advanced systems are developed with meaningful user participation from inception to ensure alignment with the priorities and needs of the blind and low vision community, thereby increasing user acceptance and practical utility (Martiniello et al., 2023).

Exploration of real-time object detection and collision avoidance systems for visually impaired individuals, using sensors such as ultrasonic, LiDAR, or radar.

Despite these technological advancements, the efficacy of such systems is highly dependent on the accuracy of the applied fusion methods, necessitating robust algorithms to integrate data from diverse sensors effectively under various environmental conditions (Oladele et al., 2021). Future research must address how real-time object detection and collision avoidance systems can be optimized to meet the specific demands of navigation-based tasks, including obstacle avoidance, visual identification, and geolocation, to ensure



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safe and independent travel (Martiniello et al., 2023). A key challenge remains in ensuring these systems are both accurate and provide timely feedback without overwhelming the user with excessive information, a common issue leading to low user acceptance in prior assistive technologies (Muhsin et al., 2023). This underscores the critical need for a human-centered design approach, involving individuals with visual impairments in every stage of development, to create solutions that are not only technologically advanced but also practically usable and psychologically comfortable (Martiniello et al., 2023) (Muhsin et al., 2023). Moreover, ongoing advancements in multi-sensor data fusion techniques offer promising avenues for developing more sophisticated and reliable navigation aids, yet a comprehensive comparative analysis between research literature and commercial applications remains an underexplored area (Theodorou et al., 2023). Thus, there is a clear imperative for future work to benchmark the performance of emerging multi-sensor fusion algorithms against established commercial solutions to identify optimal strategies for real-world deployment (Ikram et al., 2024). Collision avoidance systems for visually impaired individuals using sensors In particular, real-time image processing, often powered by deep learning, is critical for accurately detecting and classifying obstacles in dynamic environments to provide timely feedback to users (He & Saha, 2023) (Theodorou et al., 2023). This necessitates ongoing research into enhancing the robustness and efficiency of object detection algorithms, particularly for distinguishing between various types of obstacles and recognizing them in overcrowded or rapidly changing scenes (Farooq et al., 2022) (Ikram et al., 2024). The integration of sensor fusion techniques, leveraging data from cameras, LiDAR, and RADAR, is crucial for improving the cognitive capabilities of autonomous systems, including those designed for assistive mobility, in navigating



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complex and dynamic environments (Nawaz et al., 2023). This interdisciplinary approach, drawing parallels with autonomous vehicle technology, holds significant promise for developing more sophisticated and adaptable navigation aids for the visually impaired (Toro et al., 2021). This paradigm shift towards intelligent, sensor-rich environments also necessitates a re-evaluation of how visual information is translated into actionable haptic or auditory feedback, moving beyond simple warnings to provide nuanced spatial awareness.

Investigation of auditory navigation aids, such as real-time audio feedback systems that guide the user through audio cues about their environment.

This could involve exploring the efficacy of personalized soundscapes and spatialized audio in conveying complex environmental information, moving beyond basic beeps and recorded instructions (Muhsin et al., 2023). Further research should investigate the optimal balance between information richness and cognitive load in auditory feedback, ensuring that users receive sufficient detail to navigate effectively without experiencing sensory overload (Ikram et al., 2024). Moreover, the integration of haptic feedback, often delivered through vibration motors, can augment auditory cues by providing tactile information about object proximity or surface changes, further enriching the navigational experience (Muhsin et al., 2023) (Farooq et al., 2022). This multi-modal approach, combining auditory and haptic feedback, has the potential to significantly enhance situational awareness and independence for visually impaired individuals, aligning with efforts to improve accessibility through machine learning and computer vision (Shukurov, 2024) (Okolo et al., 2025). One such innovation, VocalEyes, exemplifies this by converting



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live video input into audio descriptions of objects, pedestrians, and barriers, along with their estimated distances, thus enhancing environmental perception through vision-language models (Chavan et al., 2024). However, challenges remain in refining the natural language generation capabilities of these models to provide sufficiently detailed, yet concise, descriptions for real-time navigation (Choi et al., 2025). Consequently, future work should focus on optimizing the trade-off between descriptive richness and computational efficiency to ensure that auditory navigation aids remain both informative and responsive in dynamic environments.

User studies on the usability and accessibility of wearable technologies for the blind and visually impaired.

Further research should explore how these devices are integrated into daily routines and their impact on independent mobility and social participation. This includes investigating how various feedback modalities (e.g., haptic, auditory, or a combination) influence cognitive load and navigational performance in different environmental contexts (Choi et al., 2025). Moreover, the long-term cognitive load imposed by such systems, particularly those requiring complex interpretation of auditory or haptic cues, often leads to user abandonment, highlighting the need for intuitive and low-burden interfaces (Oladele et al., 2021). This necessitates a comprehensive analysis of user-centric design principles, ensuring that assistive technologies not only provide accurate navigational information but also present it in a manner that minimizes cognitive effort and maximizes natural interaction, thereby fostering greater acceptance and sustained use (Meinhardt et al., 2025). Furthermore, exploring diverse user responses to auditory cues and adapting



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feedback based on individual perception could enhance the device's efficacy and user satisfaction (Nadolskis, 2021). Such personalization of auditory feedback has been shown to improve the quality of life and enhance user experiences for individuals with visual impairments (Wang et al., 2024). The exploration of multimodal feedback, combining auditory with haptic or even olfactory cues, could further enhance spatial awareness and reduce cognitive load, offering a richer and more intuitive navigational experience for blind and low-vision individuals (Wang et al., 2024). However, a significant gap remains in understanding the accessibility of locomotion techniques within virtual reality for sensory-impaired individuals, an area largely overlooked by both academia and industry (Anderton et al., 2024). This gap highlights the necessity for further in-depth research into locomotion accessibility, including the categorization of individual techniques and their combinatorial effects, especially given the increasing complexity of applications and diverse user needs in virtual environments (Anderton et al., 2024). Designers of virtual environments also need robust tools to express layout constraints that guarantee the soundness of the VE regardless of the physical space it is experienced in (Cardoso & Perrotta, 2019). This necessitates a concerted effort to develop standardized accessibility guidelines for VR environments, moving beyond merely anecdotal evidence to incorporate empirical data on how different impairments interact with locomotion techniques (Anderton et al., 2024).

Research into the human factors in the design of assistive devices, focusing on comfort, ease of use, and learning curve.

Moreover, the integration of optional accessibility features, allowing users to customize their experience, is crucial for accommodating diverse needs and preferences



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(Dudley et al., 2023). This includes developing a comprehensive library of auditory cue materials, expanding beyond existing options to offer a broader range of choices that can be tailored to individual user preferences and cultural contexts (Wang et al., 2024). Such customization ensures that assistive technologies are not only functional but also personally resonant, thereby enhancing long-term adoption and user satisfaction. Additionally, future research should explore the development of adaptive algorithms that can dynamically adjust feedback mechanisms based on real-time environmental conditions and individual user performance, further optimizing the balance between information richness and cognitive burden (Sahoo & Choudhury, 2023). This adaptive approach would also allow for a more nuanced understanding of how different users interact with assistive devices, fostering a more inclusive design process that considers a broader population of users (Dudley et al., 2023). Human factors perspective is crucial, as assistive technologies often involve complex interactions between users, systems, contexts, and content, necessitating interdisciplinary collaborations for effective development (Zheleva et al., 2024). This includes establishing conceptual structures and standardized terminology to guide developers more extensively, ideally through close engagement with the disabled community following the "Nothing About Us Without Us" principle (Dudley et al., 2023). This approach is vital for ensuring that assistive technologies genuinely meet the diverse needs of individuals with disabilities, moving beyond superficial accessibility to truly inclusive design practices (Ortiz-Escobar et al., 2023). Ultimately, this fuels social sustainability, providing equal opportunities without prejudice, as urged by the sustainable development goals (Bonello et al., 2023). Comfort of the user is paramount, extending beyond mere physical ergonomics to encompass psychological comfort, ensuring that



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devices are unobtrusive and reduce stigma associated with their use (Hutson, 2023). This holistic perspective of comfort is vital for promoting prolonged engagement and acceptance of assistive technologies within daily life. This also aligns with the observation that incorporating multiple modalities simultaneously introduces a reinforcing element, thereby lessening cognitive uncertainties and providing timely feedback (Bonello et al., 2023). Considering the user's abilities, limitations, and behavior to create devices that are not just technically sound but also user-friendly, leading to better safety, satisfaction, and effectiveness

This human-centered design approach also extends to integrating features like voice control, durability, portability, affordability, and compatibility, which are critical for the successful adoption and sustained use of assistive technologies by visually impaired individuals (Arora et al., 2024).

Furthermore, employing neuro-ergonomics and human-oriented interfaces can further enhance this human-machine symbiosis, especially for operators with disabilities, by identifying when assistance is needed and triggering adaptive system responses (Bonello et al., 2023). This approach, which prioritizes user agency and well-being over solely addressing functional deficiencies, contributes to the social sustainability aspect of Industry 5.0, advocating for inclusive design practices and empowerment (Bonello et al., 2023) (Ortiz-Escobar et al., 2023).



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User-centered design principles and testing of tactile and auditory interfaces in sensory substitution devices.

User-centered design for sensory substitution devices (SSDs) requires principles like making the system wearable and intuitive, keeping the user's hands free, and not interfering with existing senses. Moreover, the selection of appropriate interface modalities and information presentation is crucial to avoid overlap between assistive technologies and ensure optimal usability for individuals (Bonello et al., 2023). This iterative process of user feedback and device iteration is paramount, particularly in the initial design phases and early prototyping stages, to refine the technology effectively (Ortiz-Escobar et al., 2023). Such engagement with users throughout the design and development lifecycle is critical for identifying their precise needs and preferences, leading to more robust and representative outcomes (Ortiz-Escobar et al., 2023). This participatory approach ensures that assistive technologies are not merely functional but also align with the lived experiences and diverse requirements of visually impaired individuals, promoting greater acceptance and long-term utility (Ortiz-Escobar et al., 2023). This user-centric approach is particularly important for multimodal systems, which combine various input and output modalities to enhance accessibility and user experience, often addressing the diverse range of visual impairments (Muhsin et al., 2023) (Arora et al., 2024). This necessitates considering the intuitive relationship between different sensory modalities to avoid information overload and ensure seamless integration for users (Jiang et al., 2025). Common design strategies include leveraging vibrotactile feedback for spatial awareness and haptic interfaces for non-visual exploration of digital graphics (Zhao et al., 2020) (Sait et al., 2020). Focusing on the user, actively involving them throughout the design process,



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and ensuring the system is comfortable, intuitive, and simple to use Conversely, ignoring user involvement in the design and testing phases can lead to devices that fail to meet real-world needs, as evidenced by studies indicating a low percentage of assistive aids being tested with visually impaired individuals themselves (Muhsin et al., 2023) (Ortiz-Escobar et al., 2023). This highlights the critical importance of user involvement, particularly in the initial and evaluation stages, for creating adaptable and acceptable assistive tools for individuals with visual impairments (Muhsin et al., 2023) (Ortiz-Escobar et al., 2023). It also critically examines the human aspects of user experience and the challenges in translating research prototypes into widely adopted products, emphasizing the distinction needed for various degrees of visual impairment and age groups (Muhsin et al., 2023).

Testing should be iterative, involving real users to identify usability issues and gather feedback on tactile and auditory interfaces. Testing focuses on performance through tasks like navigation, object localization, and motion discrimination, using objective measures like 3D motion tracking data, alongside subjective usability assessments. These assessments are crucial for understanding the user's perception of the device's efficacy and comfort, highlighting areas for further refinement in the design process (Jiang et al., 2025). This approach not only validates the technical efficacy of the assistive technology but also ensures its practical utility and acceptance by the target population (Senjam et al., 2021) (Ortiz-Escobar et al., 2023). Furthermore, incorporating user experiences and feedback from diverse social and environmental contexts is essential to address infrastructural constraints and potential stigma associated with assistive devices, ensuring broad applicability and user satisfaction (Ortiz-Escobar et al., 2023). The continuous involvement



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of visually impaired participants in usability evaluations, especially for multi-modal systems, is vital to address persistent challenges and limitations (Muhsin et al., 2023) (Ortiz-Escobar et al., 2023).

METHODS AND MATERIALS

Methods

Research Design/Methods

The main process translates visual/environmental data to audio/haptic via stereo projection to point clouds, spectrograms, and binaural output. Secondary processes network users via IoT for sensor/actuator/API interactions (e.g., maps, weather). Qualitative research tests comfort, overload, and modularity through user experiments: Physical proficiency (obstacle navigation, movement detection, ball catching); Digital proficiency (communication, browsing). Timeline: Concept (Aug 2025), Prototype (Sep 2025), Testing (Oct 2025), Paper/Defense (Nov 2025). Ethical considerations: Informed consent, privacy via API security, inclusivity in design.

Materials

Materials and Processes

Inputs Visual via cameras, audio/commands via microphone. Processes Convert to 3D environment/point clouds, emulate human shortcuts (logarithmic changes, focus prioritization), apply equal-loudness contours, Fourier transform to audio. Outputs Selected audio slices. Data flow is from Stereo images → Depth map (Q matrix) → Point cloud (X,Y,Z) → Scaled virtual map → Prioritized info → Spectrogram/audio.



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Hardware Material Specification

Quantity	Material	Description
1	Raspberry PI 5, 8GB RAM	Main controller
1	UPS Hat	Power supply
2	OV5640 USB Camera 5MP and 160° POV	Image input
1	Wired Binaural Earphone with Microphone	Audio input and output
1	SIM808 with GPS	Internet and GPS access
1	IMU	Orientation detection

Table 1 : Hardware Specification

Software Specifications

To format the SD card, a bash script is executed through Ubuntu a Debian-based linux operating system to install Raspberry PI into the SD card, the main program for the device uses C++ has the main program running OpenCV to process the images and virtual worlds. In the server the device is connected to, it runs DenoJS and Puppeteer to keep track of IoT data and run automation scripts connecting to other services like Meta, or Ollama of AI

Software	Description
GitHub	Version Control
Microsoft Word	Documentation



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Linux (Modified Raspberry PI OS)	Operating System
OpenCV (C++)	Image Processing
DenoJS	IoT Central Server
Ollama	IoT Server Assistant
MediaPipe	Hand gesture recognition
WhisperX	Voice command recognition
VSCode	IDE

Table 2 : Software Specification

Library and Board Managers



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REFERENCES

- (n.d.). Retrieved from AuralVision: <https://auralvision.org/>
- (1980). In M. I. Posner, *Orienting of Attention* (pp. 32(1), 3-25). Quarterly Journal of Experimental Psychology.
- Akshay Vijay Panchal, M. C. (2024, April 27). *Clearway Companion - an Ai Powered Aid for Visually Impaired.* Retrieved from SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4809356
- Cristina Eusebio, H. K. (2007, December). *Rapid assessment of avoidable blindness in Negros Island and Antique District, Philippines.* Retrieved from ResearchGate: https://www.researchgate.net/publication/6268823_Rapid_assessment_of_avoidable_blindness_in_Negros_Island_and_Antique_District_Philippines
- Cruz, B. D. (2023, March 13). *Population of visually impaired in Iloilo City.* Retrieved from Freedom of Information Philippines: <https://www.foi.gov.ph/requests/population-of-visually-impaired-in-iloilo-city/>
- Cubillan. (2025, May 27). *Perfect Vision and Eye Health in the Philippines.* Retrieved from Shinagawa Lasik & Aesthetics: <https://shinagawa.ph/perfect-vision-and-eye-health-in-the-philippines/>
- Devi Udayakumar, S. G. (2025, May 30). *Artificial intelligence-powered smart vision glasses for the visually impaired.* Retrieved from National Center for Biotechnology Information: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12178407/>



COLLEGE OF TECHNOLOGY

Eyesynth NIRRA. (2021). EE Journal. Retrieved from RealSense:

<https://realsenseai.com/case-studies/powering-sonic-vision-for-the-blind/>

Farina, M. (2013, April 4). Neither touch nor vision: sensory substitution as artificial synesthesia? In M. Farina, *Biology & Philosophy* (pp. 32(4), 639-655). Springer Nature. Retrieved from PhilArchive: <https://philarchive.org/rec/FARNTN>

Fechner, G. T. (1960). *Elemente der Psychophysik*. Breitkopf und Härtel.

Fleck, A. (2024, January 4). *Vision Loss Predicted to Surge 55% by 2050*. Retrieved from Statista: <https://www.statista.com/chart/31502/expected-number-of-people-with-vision-loss-globally/>

Giles Hamilton-Fletcher, J. A. (2021, July 2). *SoundSight: a mobile sensory substitution device that sonifies colour, distance, and temperature*. Retrieved from Home | SpringerLink: <https://link.springer.com/article/10.1007/s12193-021-00376-w>

Hoffmann, R. M., Spagnol, S. P., Kristjánsson, Á. P., & Unnþorsson, R. P. (2018, September). *Evaluation of an Audio-haptic Sensory Substitution Device for Enhancing Spatial Awareness for the Visually Impaired*. Retrieved from Optometry and Vision Science: https://journals.lww.com/optvissci/fulltext/2018/09000/evaluation_of_an_audio_haptic_sensory_substitution.10.aspx

Jakob Kilian, A. N. (2022, February 26). *The Unfolding Space Glove: A Wearable Spatio-Visual to Haptic Sensory Substitution Device for Blind People*. Retrieved from PubMed: <https://pubmed.ncbi.nlm.nih.gov/35271009/>



COLLEGE OF TECHNOLOGY

Jamie Ward, P. M. (2010). Visual experiences in the blind induced by an auditory sensory substitution device. In P. M. Jamie Ward, *Consciousness and Cognition* (p. March). ELSEVIER.

Jr., M. J. (2024, April 8). *Country report from the Philippines to the mid-term regional general assembly, Thailand, 27-29 November 2023*. Retrieved from World Blind Union - Asia Pacific: <https://wbuap.org/archives/1587>

Junchi Feng, G. H.-F.-R. (2024, August 26). *Haptics-based, higher-order Sensory Substitution designed for Object Negotiation in Blindness and Low Vision: Virtual Whiskers*. Retrieved from arXiv: <https://arxiv.org/abs/2408.14550>

Ligao Ruan, G. H.-F.-R. (2025, February 1). *Multi-faceted sensory substitution using wearable technology for curb alerting: a pilot investigation with persons with blindness and low vision*. Retrieved from Taylor & Francis Online: <https://www.tandfonline.com/doi/full/10.1080/17483107.2025.2463541>

Lijuan Que, Z. Q. (2025, April 29). *An analysis of the global, regional, and national burden of blindness and vision loss between 1990 and 2021: the findings of the Global Burden of Disease Study 2021*. Retrieved from Frontiers | Publisher of peer-reviewed articles in open access journals: <https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2025.1560449/full>

Louis Commère, J. R. (2023, April 11). *Evaluation of short range depth sonifications for visual-to-auditory sensory substitution*. Retrieved from arXiv: <https://arxiv.org/abs/2304.05462>



COLLEGE OF TECHNOLOGY

Macpherson, F. (2018). Sensory substitution: A new perceptual experience? In F. Macpherson, *Sensory Substitution and Augmentation* (pp. 162-174). Oxford University Press.

Maidenbaum, S. (2015, October 26). *Sensory Substitution Training for Users Who Are Blind with Dynamic Stimuli, Games and Virtual Environments*. Retrieved from ACM Digital Library: <https://dl.acm.org/doi/10.1145/2700648.2811324>

Memoona Sami, D. A. (2024, December). *Efficient Object Detection and Voice-Assisted Navigation for the Visually Impaired: The Smart Hat Approach*. Retrieved from Sukkur IBA Journals: <https://journal.iba-suk.edu.pk:8089/SIBAJournals/index.php/sjcms/article/view/1535/469>

Norman, D. (2013). *The Design of Everyday Things*. New York: Basic Books.

Norton, H. (2024, September 12). *The most and least visually impaired countries worldwide*. Retrieved from Compare the market: <https://www.comparethemarket.com.au/health-insurance/features/visually-impaired-countries-2024/>

Otilia Zvorășteanu, S. C.-G. (2021, July 6). *Sensory Substitution for the Visually Impaired: A Study on the Usability of the Sound of Vision System in Outdoor Environments*. Retrieved from MDPI - Publisher of Open Access Journals: <https://www.mdpi.com/2079-9292/10/14/1619>

Paul Bach-y-Rita, S. W. (2003). Sensory substitution and the human-machine interface. In S. W. Paul Bach-y-Rita, *Trends in Cognitive Sciences* (pp. 7(12), 541-546). Cell Press.



COLLEGE OF TECHNOLOGY

Shachar Maidenbaum, S. H.-R.-T. (2014, December 1). *The “EyeCane”, a new electronic travel aid for the blind: Technology, behavior & swift learning.* Retrieved from Sage Journals: <https://journals.sagepub.com/doi/abs/10.3233/RNN-130351>

W.H.O. (2023, August 10). *Blindness and vision impairment.* Retrieved from World Health Organization: <https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment>

Yiming Zhao, S. Y. (2025, April 29). *Evaluation of the Efficacy of an Assistive Device for Blind People: A Prospective, Non-Randomized, Single Arm, and Open Label Clinical Trial.* Retrieved from Taylor & Francis Online: <https://www.tandfonline.com/doi/full/10.1080/02713683.2025.2495212>

Yon, D. K. (2025, June 25). *Global burden of vision impairment due to age-related macular degeneration, 1990–2021, with forecasts to 2050: a systematic analysis for the Global Burden of Disease Study 2021.* Retrieved from PubMed Central: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12208786/>

Zaidao Han, S. L. (2025, August 27). *Multi-path sensory substitution device navigates the blind and visually impaired individuals.* Retrieved from ScienceDirect: <https://www.sciencedirect.com/science/article/pii/S0141938225002379>