

World Navigation Hat - Development of a Wearable Navigation Aid using AIoT for the Visually Impaired

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Abstract—Our primary objective is aligned with Sustainable Development Goal (SDG) 10 on reducing inequalities, specifically to mitigate disparities faced by visually impaired individuals (VIP) by addressing a key challenge in sensory substitution devices (SSDs): sensory limitations. We hypothesize that enabling user-controlled selection of substituted sensory information via intuitive inputs like hand gestures could facilitate efficient subconscious pattern-building in the brain, thereby minimizing overload, fatigue, and integration issues. To test this, we developed a wearable prototype using a Raspberry Pi 5 equipped with a UPS, IMU sensor, camera, and earphones, designed as a head-mounted “hat” to distribute weight away from sensitive facial areas. The system generates depth maps using MiDAS AI for environmental perception, recognizes hand gestures via MediaPipe AI for user control, and employs a novel algorithm to produce targeted audio channels representing selective visual data by emulating human sensory processes in psychology, plus a primitive connection to a server through NodeJS for future modular features. Validation involved empirical assessments of sensory limitations through metrics including sensory overload (e.g., interpretation accuracy), fatigue (e.g., sustainable usage duration), integration (e.g., reaction times and learning curves), and overall device performance. Extensive optimizations were required, such as model downscaling, information chunking into digestible segments, and consideration of alternatives like stereo vision to enhance real-time efficiency. Results indicate that users favored brief, intermittent audio outputs over prolonged sessions, demonstrated improved environmental perception, and experienced reduced sensory limitations. In conclusion, our approach partially resolves SSD challenges, validating the potential of controllable substitution, though further refinements and longitudinal studies are essential for broader applicability and impact on SDG 10 targets.

Index Terms—sensory substitution device, SDG 10, visual impairment, controllability, accessibility, assistive robotics, industrial automation

I. INTRODUCTION

Visual impairment is a global health problem that significantly affects individual's daily lives by impeding independent navigation, social interaction, and overall quality of life [1]. 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 [2]. This thesis focuses on SDG 10, which aims to reduce inequalities within and among countries based on income, sex, age, disability, sexual orientation, race, class, ethnicity, religion, and opportunity [3]. More specifically our thesis focuses on visual impaired people or VIPs under disability, VIPs does not pertain to total blindness and can be identified and categorized based on presenting visual acuity [2].

Navigation is one of the problems VIPs encounter; they often have difficulty crossing the road and tracking their location, as well as experiencing accidents, falls, and collisions [4]. In addition, VIPs experience social isolation and reduced access to information, limiting their educational and employment opportunities [5]. There are already existing solutions or aids for VIPs, for daily assistance, which include guide dogs, white canes, and electronic travel aids [4]. Additionally, one of the technologies VIPs depend on for navigation is assistive devices, which use sensory substitution to convert visual information into auditory or tactile cues to provide spatial awareness often incorporate IoT sensors to capture real-time environmental data, providing navigational assistance in complex environments [6].

Sensory substitution devices or SSDs are assistive wearable devices that can be eyewear, a vest, or a hat, allowing VIP

users to perceive their surroundings by converting sensory information from one modality to another [7]. For our thesis we will focus on developing a SSD that is a hat. These SSDs are embedded with sensors that allow obstacle detection, navigation, and object recognition, enhancing VIPs' daily independence and reducing their reliance on traditional aids [8]. However, global adoption of these devices is limited due to cognitive overload performance, extensive training needs, ergonomic discomfort design, and the lower processing bandwidth of non-visual senses compared to vision [9]. This is what our thesis will focus on, to experiment to see if by implementing controllable selective substitution that we could overcome this sensory limitation.

A. Problem Identification

This thesis addresses a global problem aligned with the United Nations Sustainable Development Goal (SDG) 10, which is to reduce inequalities within and among countries based on income, sex, age, disability, sexual orientation, race, class, ethnicity, religion, and opportunity [3]. Specifically, our target problem is to make it possible for visually impaired persons (VIPs) to have approximately the same level of opportunities as the general population [10] by minimizing the major limitations currently faced by sensory substitution devices (SSDs), thereby contributing to the achievement of several SDG 10 targets.

The inequalities the VIPs faced we specifically focused on are two major but often overlapping categories: navigational and social [16]. Navigational inequalities which are barriers in physical and digital infrastructure not designed for accessibility such as building that lack tactile guides or website and software without audio alternatives [17]. Social inequalities which are limitations in communication, societal status, or workforce participations, for instance only about 44% of visually impaired individuals are employed compared to 79% of those without disabilities, often due to employer attitudes and lack of accommodations [18]. These two categories of inequalities could be minimized if the VIPs partially have the ability they lack, this could be achieved through Sensory Substitution Devices [19].

B. Research Objectives and Contributions

The primary objective of this research is to minimize inequalities for visually impaired individuals by developing and testing substitution technologies, specifically sensory substitution devices (SSDs) that convert visual information into accessible formats like audio, thereby enabling more independent navigation and social interaction [4]. This approach prioritizes substitution to address core sensory gaps holistically, while acknowledging potential hybrids with assistive elements, and aligns with SDG 10 by promoting economic inclusion through expanded job opportunities (Target 10.1), empowerment via regained access and participation (Target 10.2), and equal opportunities by reducing discriminatory barriers (Target 10.3) [3].

The key novelty in solving the sensory limitation issues that SSDs face is through incorporating controllability for selective perception [20]. This idea is inspired by psychological principles where the human sense filters relevant information to avoid overload [21]. To accomplish this our device should allow the sensory translation to be controlled by the user like through hand gestures, allowing realtime customization of translation and addressing the Sensory limitation issue of SSDs like overload, fatigue, or integration [9]. By demonstrating that this is possible, it could pave the way for scalable applications to other sensory disabilities, enhancing the fields of assistive technology with user-centered, efficient substitution framework [22].

II. RELATED WORK

There are existing solutions in providing VIPs a way to navigate the world, but from our research there are two major overlapping categories of these solutions which are Assistive and Substitution technologies [4]. Assistive technologies which primarily extend existing capabilities such as canes, guide dogs, or braille displays [26]. Substitution technology which primarily represent missing senses through alternatives such as screen readers and sensory substitution devices that convert visual data to audio feedback [20]. Since our thesis aims to minimize inequalities of the VIPs by providing them a way to navigate the physical and digital world so that they could have approximately the same opportunities as the general population, we focused on Substitution technology, more specifically visual substitution devices [27].

A. Assistive and Substitution Technologies

Reference [20] designs their SSD for blindness using touch and audio, similarly following design principles like task-focused information conveyance to avoid redundancies and match the sensory bandwidths, highlighting the issues faced by SSDs like sensory overload from excessive data so there must be a selective process of key environmental cues to mitigate it. The bandwidth mismatches does lead to persistent fatigue and high training requirements delay usability and integration. Reference [23] introduces a multi-device combination SSD, lowers overload by distributiong cognitive load, enhances integration through perceptual reweighting, and improving long-term navigation accuracy. The initial dual-use however, increases fatigue without extended training, highlighting integration challenges for less experienced users. Reference [24] reviews vision substitution via hearing and touch, implements preprocessing filters to reduce overload by focusing on essential data, plasiticity aids long-term integration, and enables better nativation equity. The bandwith limits still causes persistent information loss and fautigue, often struggling with controllability and requires user adaption. Reference [25] device similarly is also a wearable portable smart hat, is low-cost, minimizes navigational inequalitess, and provides real-time feedback to improve integration and learning. It lacks selective processing and can lead to sensory overloading in

cluttered environments and can cause fatigue over prolonged use.

B. Gaps in Addressing Sensory Limitations

These SSDs highlights and face a common issue which we can generally call as Sensory Limitation, these include sensory overload where the translated information is just too much for the user to actually process either through auditory bandwidth limit or interference, sensory fatigue where hearing audio repetitively can cause discomfort and less sensory perception, and finally sensory integration where the translated audio representation can't be subconsciously integrated by the user's perception of their environment making learning harder and daily use tiring [20]. Our thesis aims to minimize sensory limitation through high controllable selective translation where specific environment cues can be selectively filtered by the user directly and for any period of time, minimizing overload, fatigue, and allowing more controllable integration like allowing modular learning when using it for the first time [23].

III. METHODOLOGY

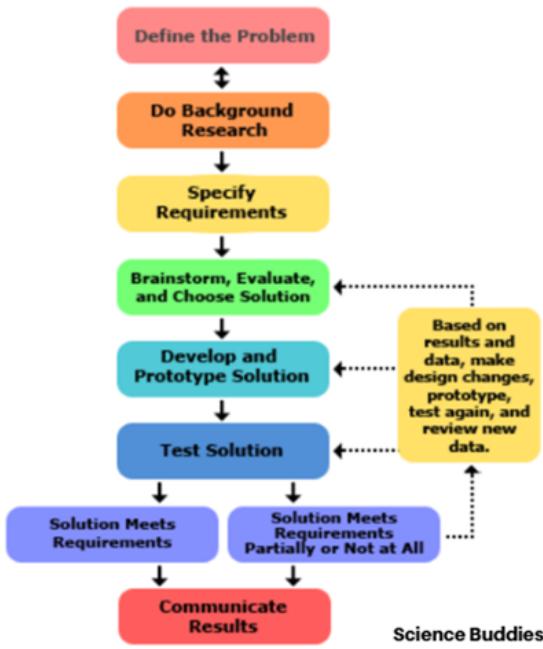


Fig. 1. Engineering Design Process

The method for this study follows the engineering design process as seen in figure 1, we defined the problem by aligning it with SDG 10 and limited the scope to visual impairities, we did background research on solutions like sensory substitution devices. Specified the requirements to test our hypothesis, brainstorm a way to accomplish it, develop and prototype the device, test and see if it fulfilled our hypothesis, brainstorm again when the hypothesis doesn't align, else communicate the results.

A. Hypothesis and Design Principles

Following the theoretical principle that human visual perception has a focus and special resolution *Foveation* [28]. Our approach is to generate a depth map from a camera using MiDaS, the hand gesture is also captured from the same camera image using MediaPipe. The hand gesture specifically the back of the right hand determines what is to be executed by the command, for this instance it has a few pre-installed gestures:

- **Open hand gesture** which translates the depth map into audio by cycling between right and left side where each slice of the image is translated into audio with the vertical position representing frequency and depth/proximity represented by the equation

$$A_c(T, s) = \sum_{n=0}^{B-1} \frac{D_{t(T)}[B-1-n]}{255 \times 10} \cdot G_c(t(T)) \cdot \sin\left(2\pi f_n \frac{s}{R}\right) \quad (1)$$

Where:

- c - Channel number, 0 for right and 1 for left
- A_c - Audio output for channel c
- T - Time in seconds
- C - Cycle duration in seconds (*Configurable by "-cd=", default 4.0*)
- $t(T)$ - Normalizes time T to be between 0 and 1 oscillating triangularly
- $D_t[n]$ - Depth map vertical slice at horizontal position t , frequency index n (0 to 255)
- B - Number of frequency bins (*Configurable by "-nb=", default 64*)
- n - Frequency bin index (0 to $B-1$)
- $G_c(t)$ - Channel gain factors $t - 2ct + c$
- s - Sample index within the current audio block (0 to $S-1$)
- S - Block size in samples (*Configurable by "-bs=", default 512*)
- R - Sample rate in Hz (*Configurable by "-sr=", default 44100*)
- f_n - Frequency in Hz for bin n , logarithmically spaced $f_n = 100 \cdot \left(\frac{8000}{100}\right)^{\frac{n}{B-1}}$

- **Closed hand gesture** which is similar to open hand gesture but only translate the middle section of the depth map allowing the user to control the scanning at their own control, represented by the formula

$$K_c(T, s) = A_{\frac{1}{2}}(T, c) \quad (2)$$

Where:

- K_c - Audio output for channel c
- A_c - Original audio output (*open hand gesture*) for channel c

- **Call me hand gesture** calls a specific user in facebook, just to test the server API and to ensure that future continuations would allow for modular or additional applications.

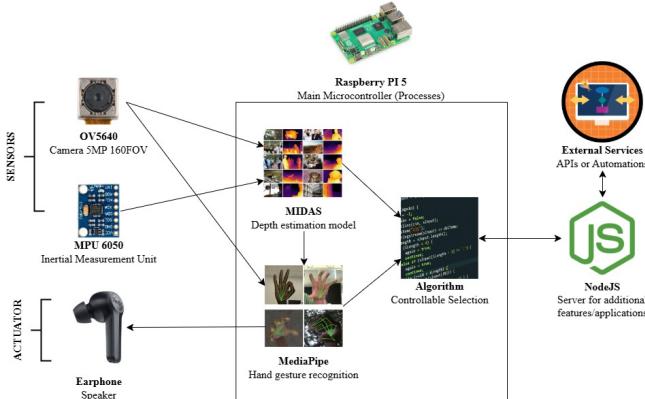


Fig. 2. System Architecture

B. System Architecture

The architecture in figure 2 shows the sensors, process, and actuators of the device. For the sensors, the camera captures the image, and the IMU assist with correction and to provide the context on where the camera is capturing from. This is fed to the first process of the device which is the depth estimation model which uses the highest MiDaS model, and is also fed to the second process of the device which is hand gesture recognition which uses MediaPipe to detect the gestures. The depth map and hand gesture are both fed into our custom algorithm that should be able to allow the user to controllably control the selection of substituted information. The algorithm also allows modular features by customizing the gesture's actions and processes, these additional processes could be sent to the server to run more computative or IoT request. The server accomplish the request by either running local processes or make additional API request to external APIs. The response of the server is received back by the device to the main algorithm. This algorithm then generates the necessary audio cues to be outputted by the speaker.

IV. EXPERIMENTAL EVALUATION

Our research conducted three separate test to indicate if we were able to minimize the sensory limitation issue, and another test to check the device performance more specifically with hand gesture recognition, the central method of controlling the system. To test for sensory overload the users are to identify the direction of the open door to ensure they could identify near (*door sides*) and far (*through the door*) items. To test for sensory fatigue a survey is tested on the users during the open door identification test to check how uncomfortable they feel during long periods of using it. To test for sensory integration the user is tested how quickly they could learn to navigate with the device. Finally for hand gesture recognition, we tested multiple times if the device is able to correctly identify the gesture multiple times in different lighting conditions. All of these test are quantitative has they have clear units of measurements except for sensory fatigue testing has it is more subjective and so is qualitative.

A. Experimental Setup

There are 20 participants which are students of the University of San Agustin who are not blind, tools/materials include a room with a door to test for user's awareness, and each individual are tested in different environments at day and night, and outside and inside.

V. RESULTS

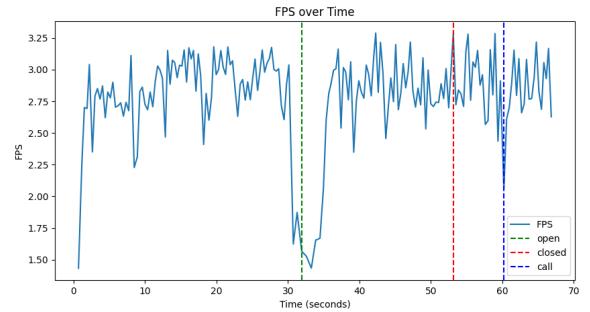


Fig. 3. FPS of image processing

During the testing we also analyzed the FPS during the different gesture modes to see if the FPS of gesture detection and depth map generation could hinder the user. Based on figure 3, the FPS in the raspberry PI 5 was around 3 FPS and spikes down during gesture changes. This wont effect the audio generation has it is in a seperate thread.

TABLE I
QUANTITY CASES OF DOOR IDENTIFICATION

Environment	Whole (<i>open hands</i>)	Front (<i>closed hands</i>)	Unable to
Near the door (<i>first time</i>)	5	11	4
Far away (<i>first time</i>)	5	5	10
Near the door (<i>10 minutes learning</i>)	6	13	1
Far away (<i>10 minutes learning</i>)	8	5	7

^a Total 20 participants based on learning duration

Table I shows that for people using it for the first time with a quick explanation that they have a $16/20 = 80\%$ accuracy when near the door (*Around 1 meter*) else $10/20 = 50\%$ accuracy when far to the door (*Around 2 meters*). After they play around for 10 minutes the accuracy increases from 80% to $19/20 = 95\%$ and from 50% to $13/20 = 65\%$, on average a $\frac{(0.95-0.8)+(0.65-0.5)}{2} = 15\%$ increase. Based on methods used show that controllability allows users to switch from whole area scanning to front area scanning based on whatever the user needs at that time showing an average increase of $\frac{\frac{13-6}{6} + \frac{11-5}{5}}{2} = 118.33\%$ when switching to front scanning if near the door, while the opposite showing an average decrease

of $\frac{\frac{5-5}{5} + \frac{5-8}{8}}{2} = 18.75\%$. From related literatures the percentage of object recognition success is around 54% after prolonged training, although our thesis is not about object detection rather more on data perception it does show higher average rates of recognition being 72.5%, indicating lower rates but not completely eliminated sensory overload.

TABLE II
MAXIMUM DURATION OF USERS UNTIL FATIGUE

Situation	30 secs	1 min	5 mins	10 mins	15+ mins
Hearing audio non-stop	6	14	0	0	0
Recovery	0	4	12	3	1
Identifying doors (from last test)	0	1	5	14	1
Navigating rooms	0	0	2	6	12

^a Total 20 participants

Table II shows how long the user could use the device without getting fatigue (*uncomfortable/annoyance/headaches*). The first test is to see how long non-stop audio could cause fatigue, it caused on average $\frac{6.30+14.60}{20} = 51 \text{ seconds}$ until user is fatigued. It then takes around $\frac{4.1+12.5+3.10+1.15}{20} = 5.45 \text{ minutes}$ for a person to feel comfortable to use the device again after fatigue. In taking the previous test it took around $\frac{1.1+5.5+14.10+1.15}{20} = 9.05 \text{ minutes}$ until the person gets tired in repetitive testing with identifying doors. And for just navigating rooms where the person can stop any audio for a long period of time, many did not even get fatigued as they could just simply lower their hand to stop any audio, but it still took 8 participants to still get fatigued after using it for around $\frac{2.5+6.10}{8} = 8.75 \text{ minutes}$, meaning the controllability really assisted in minimizing sensory fatigue.

Table I and II showed that users would take around 10 minutes to reach the plateau of sensory integration or mastery which is on average $\frac{0.95+0.65}{2} = 80\%$ success in understanding the data translated to them.

TABLE III
HAND GESTURE RECOGNIZED DATA

Gesture	No Gesture	Open hand	Closed hand	Call
No Gesture	30	0	0	0
Open hand	3	26	1	0
Closed hand	4	4	22	0
Call	3	0	5	22

^a Total 30 gestures tested

Table ?? shows how accurate the hand gesture recognition is, gestures are tested alternating to ensure that there is enough time before the model predicts the next gesture and so the lightings and situation doesn't differ if they change slowly. If there is no gestures there is a 100% accuracy, if the user puts an open hand it is around $\frac{26}{30} = 86.67\%$ accurate, often confused on no gesture. If the user puts a closed hand it is around $\frac{22}{30} = 73.33\%$ accuracy, often confused for no gesture and open hand. If the user puts a call gesture it is around $\frac{22}{30} = 73.33\%$ accurate, often confused for closed hand gesture.

This table shows the limitations in hand recognition probably because of the fingers being hidden in closed hand gestures, or the algorithm missing the two fingers in the call gesture.

VI. DISCUSSION

Based on the results it shows that we are able to minimize sensory limitation through allowing controllable selection of translated information, however among the different kinds of sensory limitation, sensory fatigue seems to be our largest issue. It's probably because sensory overload can always be minimized by chunking/breaking down information to more specific and selectable pieces of information, and learning the device can make easier by making the features more modular so that new individuals could learn and use what they need as they go, but the output is always a summation of frequencies and so even if stopped from time to time, it still causes hearing fatigue seeing how the average duration of continuous use is around 9.05 minutes. This could be even minimized in the future by transferring some of the translated information into tactile senses, regardless we are able to show that our hypothesis has some truth to it even if it doesn't completely solve the issue of sensory limitations.

A. Implications and Impact

The device shows that it could convey visual information into audio and that the information can be sliced/subsetted into what the user wants to hear, this has the implication of not only conveying visual information but also digital information like social media, other recognition systems like text recognition to speech, face recognition, or even object recognition allow this device to help the visually impaired navigate both the physical world like physical architectures, and digital worlds like websites and platforms. The device also shows that multiple gestures could be added and when we tested the call gesture it was able to trigger the mock API to call a specific user, showing modular extensions to fit the variety needs and wants of the VIPs. Hardware was not our priority rather the hypothesis, this could be implemented in existing visual device like the Meta glasses or other eyewear to make up the hardware limits and portability, such as using stereo camera and Lidar for more faster and accurate depth maps. The work could be used as a foundation to build more controllable and selective processes like implementing stereo projections, point clouds, or even eye-tracking so hand gesture would not be used.

VII. CONCLUSION

In conclusion, our findings shows that we were able to partially minimize the issues of sensory limitations, although less so with sensory fatigue. This study could forward the progress on the development of Sensory substitution devices has future researchers and inventors could take inspiration from our hypothesis. By implementing these findings in more industrial technologies like eyewear, the visually impaired could possibly one day have approximately the same opportunities as the general population minimizing the navigational

and societal inequalities faced by them, and by extension any disability regarding senses could be benefited from this study.

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