Article

Low-Cost Open Source Ultrasound-Sensing Based Navigational Support for Visually Impaired

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Abstract: Nineteen million Americans have significant vision loss. Over 70% of these are not employed full-time, and more than a quarter live below the poverty line. Globally, there are 36 million blind people, but less than half use white canes or more costly commercial sensory substitutions. The quality of life for visually impaired people is hampered by the resultant lack of independence. To help alleviate these challenges this study reports on the development of a low-cost (<$24), open-source navigational support system to allow people with the lost vision to navigate, orient themselves in their surroundings and avoid obstacles when moving. The system can be largely made with digitally distributed manufacturing using low-cost 3-D printing/milling. It conveys point-distance information by utilizing the natural active sensing approach and modulates measurements into haptic feedback with various vibration patterns within the distance range of 3 m. The developed system allows people with lost vision to solve the primary tasks of navigation, orientation, and obstacle detection (>20 cm stationary, moving up to 0.5 m/s) to ensure their safety and mobility. Sighted blindfolded participants successfully demonstrated the device for eight primary everyday navigation and guidance tasks including indoor and outdoor navigation and avoiding collisions with other pedestrians.

Keywords: 3D printing; additive manufacturing; assistive devices; blind; obstacle avoidance; sensors; sensory substitution; ultrasonic sensing; ultrasound sensing; visually impaired

1. Introduction

According to the World Health Organization (WHO) [1], approximately 1.3 billion people live with some form of vision impairment, and 36 million of them are totally blind. The vast majority of the world's blind population (around 87%) live in developing countries [1, 2]. In addition, this challenge is falling on the elderly at an increasing rate, with the group of visually impaired people over 65 years of age growing with a per-decade increase of up to 2 million persons, which is faster than the overall population with visual impairments [2]. However, even in developed countries like the U.S. this is becoming an increasing problem because of several factors. First, the U.S. is aging: Americans 65 and older is projected to more than double from 46 million today to over 98 million by 2060, and their share of the total population will rise to nearly a quarter from 15% [3]. Second, the elderly in the U.S. are increasing financially vulnerable [4]. According to American Foundation for the Blind [5] and National Federation of the Blind [6], more than 19 million American adults between the ages of 18 and 64 report experiencing significant vision loss. For working age adults reporting significant vision loss, over 70% are not employed full-time, and 27.7% of non-institutionalized persons aged 21 to 64 years with a visual disability live below the poverty line [6].

Safe navigation and independent mobility are parts of everyday tasks for visually impaired people [7], and can only partially be resolved with the traditional white cane (or their alternatives such as guide canes or long canes). According to several studies [8, 9], less than 50% of the blind population use white canes. For those that do use them, they work reasonably well for short distances as they allow users to detect obstacles from the ground to waist level [10].

Over the past few decades, several approaches have been developed to create sensory augmentation systems to improve the quality of life of people with visual impairments, which will be reviewed in the next section. It is clear developing a sensor augmentation or replacement of the white cane with a sensory substitution device can greatly enhance the safety and mobility of the population of people with lost vision [11]. In addition, there are sensory substitution products that have already been commercialized that surpass the abilities of conventional white canes. However, a small number of commercially available sensory substitution products are not accessible to most people from developing countries as well as the poor in developed countries due to costs: i) UltraCane ($807.35) [12], an ultrasonic-based assistive device with haptic feedback and the range of 1.5 to 4 meters; ii) Miniguide Mobility Aid ($499.00) [13], a handheld device that uses ultrasonic echolocation to detect objects in front of a person in the range of 0.5 to 7 meters; iii) LS&S 541035 Sunu Band Mobility Guide and Smart Watch ($373.75) [14] that uses sonar technology to provide haptic feedback regarding the user's surroundings; iv) BuzzClip Mobility Guide ($249.00) [15], a SONAR-based hinged clip which has three ranges of detection (1, 2, and 3 meters) and provides haptic feedback; v) iGlasses Ultrasonic Mobility Aid ($99.95) [16] provides haptic feedback based on ultrasonic sensors with the range of up to 3 meters, vi) Ray [17] complements the long white cane by detecting barriers up to 2.5 meters and announces them via acoustic signals or vibrations. It is thus clear that a low-cost sensor augmentation or replacement of the white cane with a sensory substitution device is needed.

One approach recently gaining acceptance for lowering the costs of hardware-based products is the combination of open source development [18-20] with distributed digital manufacturing technologies [21, 22]. This is clearly seen in the development of the open source self-replicating rapid prototyper (RepRap) 3-D printer project [23-25], which radically reduced the cost of additive manufacturing (AM) machines [26] as well as products that can be manufactured using them [27-29] including scientific tools [19, 30-34], consumer goods [35-40], and adaptive aids [41]. In general, these economic savings are greater for the higher percentage of the components able to be 3-D printed [42, 43].

In this study, a low-cost, open-source navigational support system using ultrasonic sensors is developed. The system can be largely digitally manufactured including both the electronics and mechanical parts with conventional low-cost RepRap-class PCB milling [44] and 3-D printing. The system is quantified for range and accuracy to help visually impaired people in distance measurement and obstacle avoidance including the minimal size of the object. Sighted blindfolded participants tested the device for primary everyday navigation and guidance tasks including: 1) walk along the corridor with an unknown obstacle, 2) bypass several corners indoors, 3) walk through the staircase, 4) wall following, 5) detect open door, 6) walk along the sidewalk in the street, 7) bypass an obstacle on the street and 8) avoid collisions with pedestrians.

2. Background on Sensory Augmentation Systems for Visually Impaired

In the most recent comparative survey of sensory augmentation systems to improve the quality of life of people with visual impairments [45], assistive visual technologies are divided into three categories: 1) vision enhancement, 2) vision substitution, and 3) vision replacement. In addition, Elmannai et al. [45] provided a quantitative evaluation of wearable and portable assistive devices for the visually impaired population. Wahab et al. [46] developed a “Smart Cane” device based on ultrasonic sensors, servo motors, and fuzzy controller to detect obstacles and provide haptic feedback with audio instructions for navigation. Fonseca et al. [47] proposed an ultrasonic-based long cane with micro-motor actuator to provide frequency-modulated vibration feedback for distance measurements. Amedi et al. [48] introduced an electronic travel aid that uses multiple infrared sensors aimed at different directions with tactile and audio output. Bharambe et al. [49] developed a sensory substitution device with two ultrasonic sensors and three vibration motors to assist people in direction and navigation. This device covers three distance ranges simultaneously and overcomes the issue of narrow cone angle [49]. Kumar et al. [50] presented an ultrasonic-based cane to help blind people. Yi et al. [51] developed an ultrasonic-based obstacle avoidance system with feedback and guidance in the form of audio messages. Pereira et al. [10] proposed a wearable jacket as a body area network for obstacle detection based on ultrasonic sensors and Mica2 sensor nodes. Aymaz and Çavdar [52] introduced an assistive headset to navigate visually impaired people based on measurements from four ultrasonic sensors. In [53] the authors developed ultrasonic smart glasses.

In addition to the devices based on the use of acoustic waves, there are also a number of devices using more complex computer vision and GPS/GSM systems. Landa-Hernandez et al. [54] proposed a complex guidance system in indoor areas. The system has a detection range of 4 meters and consists of two video cameras and a laptop to calculate the distance to obstacles with the help of fuzzy decision rules [54]. The authors in [55] presented a wearable aid system for blind people, which consists of image sensors and acoustic module governed by a field programmable gate array. It processes the environmental information for locating objects and converts this information to sounds that will be received by stereophonic headphones [55]. A concept of Path Force Feedback belt was proposed by Oliveira [56]. The main unit uses two video cameras to capture the video stream, generates a 3-D model of the user's environment, and provides vibration feedback. An obstacle avoidance system within the range of 0.8-4 m using Microsoft Kinect depth camera was presented by [57]. Aladren et al. [58] introduces a navigator with integrated range and visual information to guide people through structured environments. The device located on the user's neck and connected with a laptop packed in a backpack [58]. Mocanu et al. [59] developed a wearable device to help visually impaired people to navigate in unknown environment using the machine learning and computer vision techniques. By adopting GSM and GPS coordinator, image sensor, light and temperature sensors, and SONAR, Prudhvi et al. [60] introduced a wearable assistive navigator in the form of a silicon glove with haptic feedback and audio guidance. Sahba et al. [61] presented a system based on radio frequency identification technology to help blind people find the other party in their meeting place.

All of these projects suffer from drawbacks related to cost and complexity and thus accessibility to the world's population of visually impaired poor people.

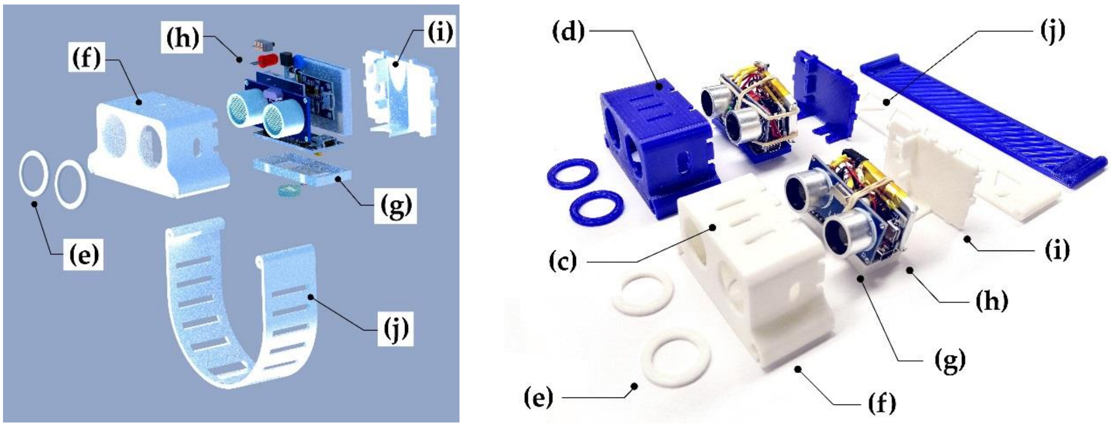
3. Materials and Methods

3.1. Design

An open-source navigational support with 3-D printable case components (Figure 1) was developed to help visually impaired people in distance measurement and obstacle avoidance. According to [45, 62], the proposed system partially fulfills the Electronic Travel Aid (ETA) requirements, which consist of providing tactile and/or audible feedback on environmental information that is not available using traditional means such as white cane, guide dog, etc.

The system is based on a 5-volt HC-SR04 ultrasonic sensor [63], which uses SONAR (originally an acronym for sound navigation ranging) to determine the distance to an object in the range of 0.02-4 m with a measuring angle of 30 degrees. It detects obstacles in front of the user's body from the ground to the head and above, and provides haptic feedback using a 10 mm flat vibration motor [64], which generates oscillations with a variable amplitude depending on the distance to the obstacle.

The device can be placed on the right or left hand, and it does not prevent the use of the hand for other tasks. It conveys point-distance information and could be used as a part of an assembly of assistive devices or as an augmentation to a regular white cane. In that way, the active sensing approach [11] was utilized, in which a person constantly scans the ambient environment. This method allows a user to achieve better spatial perception and accuracy [11] due to the similarity to natural sensory processes [65, 66].



(a) (b)

Figure 1. Parts of an open-source navigational support with 3-D printable case components: (**a**) 3D prototype; (**b**) Assembly; (**c**) Model 1 with one vibration motor; (**d**) Model 2 with two vibration motors; (**e**) Locking rings; (**f**) Case; (**g**) Vibration pad; (**h**) Sensor core; (**i**) Back cap; (**j**) Bracelet.

3.2 Bill of Materials

The system was prototyped for people with no engineering skills and the lack of available materials, so they can finish the assembly with the minimal toolkit. The bill of materials is summarized in Table 1. A 5V DC-DC boost step-up module can be considered as an optional component that can be used for battery life extension.

Table 1. Bill of materials for the open-source ultrasound-based navigational support.

Component	Quantity	Cost, USD
3-D printed case	1	0.65
3-D printed back cap	1	0.25
3-D printed bracelet	1	0.40
3-D printed vibration motor pad	1	0.05
3-D printed locking rings	2	0.05
Arduino Nano	1	3.80
Ultrasonic Sensor HC-SR04	1	1.83
Flat 10mm 3V vibration motor	1	1.40
400 mAh lithium polymer battery	1	7.49
Micro USB 5V 1A 18650 TP4056 lithium battery charger	1	1.20
*DC-DC 5V boost step-up module (optional)	*1	*5.99
Slide switch	1	0.40
0.25W 1kΩ resistor	2	<0.01
Ceramic 0.1uF capacitor	1	0.07
1N4007 diode	1	0.08
2N2222 transistor	1	0.07
5mm LED	1	0.07
Total cost, USD	**17.82** *(23.81 with optional module)	

3.3 Assembly

After 3-D printing all the necessary components, electronic parts should be soldered together following Figure 2 and assembled to a sensor core with the vibration motor.

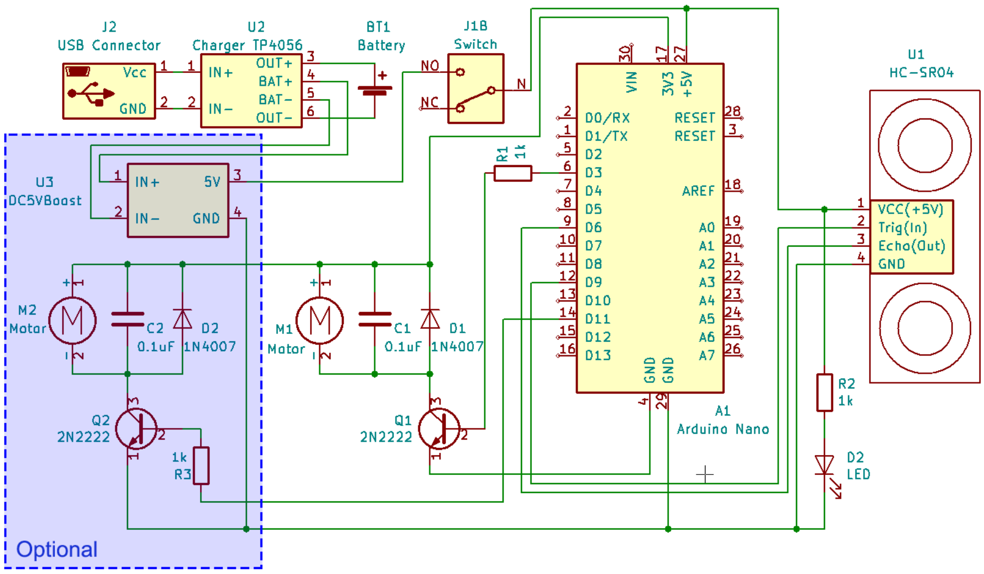


Figure 2. Electrical circuit.

The Arduino Nano board should be programmed with the code available at [67], and the electronic core assembly should be placed in the 3-D printed case to finish the whole assembly (Figure 3). All the CAD models and STL files are available online under an open-source CC BY-SA 3.0 license (Creative Commons – Attribution – Share Alike) [68]. The hand bracelet (Figure 1) has an online option for customization [69], so a person with no experience with complicated 3-D modeling software could print the part after adjusting it to their hand size. For Arduino programming, it is necessary to download free open source Arduino IDE [70].

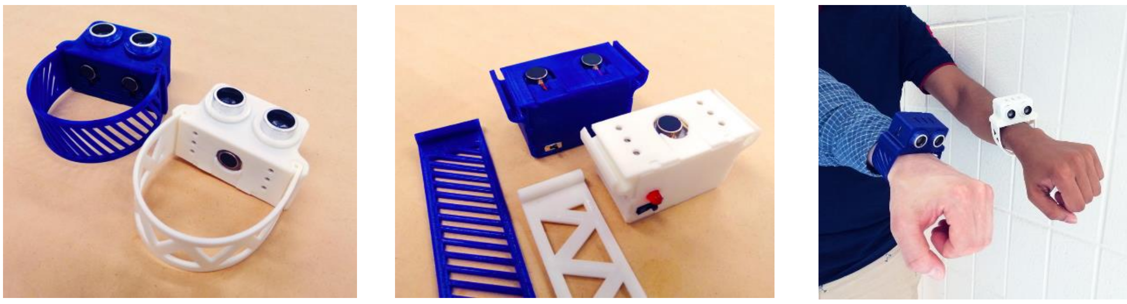


Figure 3. Assembly of an open-source navigational support with 3-D printable case components.

3.4. Operational Principles

The ultrasonic sensor emits acoustic waves at the frequency of 40 kHz, which travel through the air and reflects from objects within the working zone. It sends an 8-cycle sonic impulse at the speed of sound and its reflection from an object is received by an echo sounder [63]. The distance to the object is measured by the time delay between sending and receiving sonic impulses.

A single exponential filter [71] was used to smooth noisy sensor measurements. It processes the signal with the desired smoothing factor without using a significant amount of memory. Every time a new measured value y_t is provided, the exponential filter updates a smoothed observation, S_t:

$$S_t = \alpha \cdot y_t + (1 - \alpha) \cdot S_{t-1},\ 0 < \alpha < 1, \quad (1)$$

Where S_{t-1} – is the previous output value of the filter, y_t is a new measured value, $\alpha = 0.5$ is the smoothing constant.

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Total measurement time consists of the traveling time caused by the finite speed of sound and the delay necessary for measurements. The time delay caused by the finite speed of sound, $T_{max\ travel}$, is:

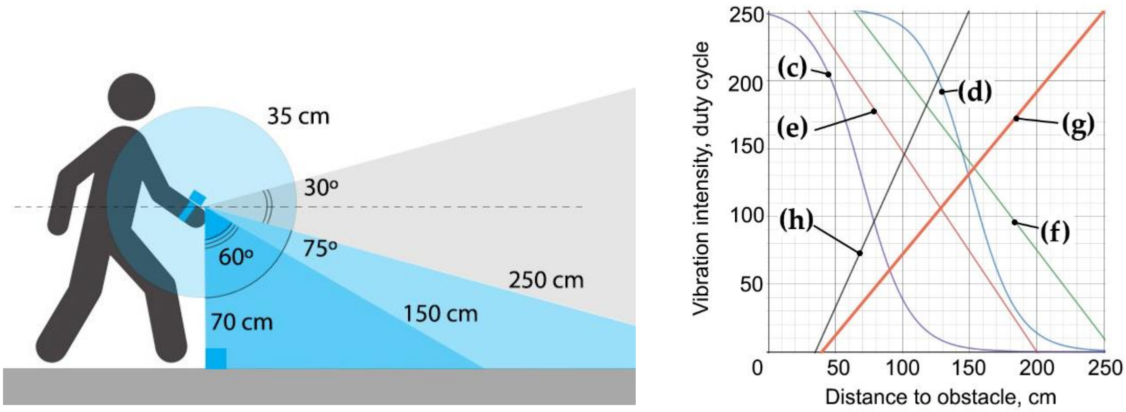
$$T_{max\ travel} = D_{max} / V_{sound} = 2 \cdot 4 / 340 = 8 / 340 = 24 \text{ (ms)}, \quad (2)$$

Where, D_{max} is the maximum measured distance to an obstacle and V_{sound} is the speed of sound in air. This results in a the maximum time delay between two consecutive measurements ($T_{max\ total\ delay}$) of:

$$T_{max\ total\ delay} = T_{max\ travel} + T_{measure} = 24 + 100 = 124 \text{ (ms)}, \quad (3)$$

Where, $T_{measure}$ is the measuring time specified in program, $T_{max\ travel}$ is the time delay caused by the finite speed of sound.

The measured distance is modulated with vibration amplitude and translated in real-time as a duty cycle parameter from the Arduino board (Figure 4). Distances up to 35 cm are characterized by single vibration pulses with a relatively high periodicity. Distances from 150 to 250 cm are characterized by single pulses with low periodicity, and distances above 250 cm are modulated with two-pulse beats.



(**a**) (**b**)

Figure 4. The ultrasonic sensor operating principles: (**a**) The principal distances (not to scale); (**b**) Calibration of the optimal duty cycle equation for the distance range of 35 cm to 150 cm, where (**c**) $M_{DC} = 127 + 127 \cdot \tanh(-(D - 70) / 35)$; (**d**) $M_{DC} = 127 + 127 \cdot \tanh(-(D - 150) / 35)$; (**e**) $M_{DC} = 296 - 1.5 \cdot D$; (**f**) $M_{DC} = 335 - 1.3 \cdot D$; (**g**) $M_{DC} = -77 + 2.2 \cdot D$; (**h**) $M_{DC} = -48 + 1.2 \cdot D$.

An optimal duty cycle equation (Figure 4, c) for the most common distance range of 35-150 cm was found during experiments and calibrations (Figure 4, b). The generated duty cycle for the Arduino output, M_{DC} is:

$$M_{DC} = m + m \cdot \tanh(-(D - k) / b) = 127 + 127 \cdot \tanh(-(D - 70) / 35),\ 0 < M_{DC} < 255, \quad (4)$$

Where m = 127, k = 70 and b = 35 are the calibrated parameters, and D is the measured distance in the range of 35 cm to 150 cm. This modulation law is based on hyperbolic tangent function, tanh, (Figure 4, c), which is close to the inverse of pain sensitization in its shape [72, 73] and demonstrated the best efficiency in most common tasks (Figure 5).

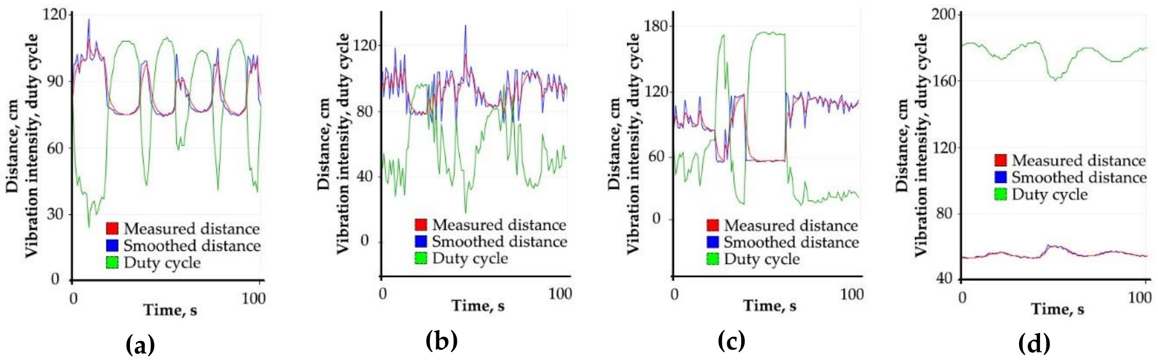


Figure 5. Calibration procedure of the duty cycle modulation based on hyperbolic tangent function (4): **(a)** Hand swinging; **(b)** Wall following; **(c)** Obstacle detection; and **(d)** Curbs tracking.

According to [74, 75], there are four major types of tactile mechanoreceptors in human skin: 1) Merkel's disks, 2) Meissner's corpuscles, 3) Ruffini endings, and 4) Pacinian corpuscles. Meissner's corpuscles respond to high amplitude incentives with low frequency and Pacinian corpuscles, in turn, respond to low amplitude incentives with high frequency. Thus, varying amplitude and frequency of vibrations, it is possible to activate these mechanoreceptors separately, which increases the working range of sensitivity levels.

Estimated current for the whole device is at the level of 50mA assuming that the vibration motor works 40% of the time. According to this, a 400 mAh battery will provide us with 8 hours of autonomous work, which is an efficient amount of time for test purposes as well as for general use if a blind person was walking throughout the entire working day.

Finally, the cost saving in percent (P) of the device was determined by

$$P = (c - m) / c \tag{5}$$

where c is the commercial cost of an equivalent device and m is the cost in materials to fabricate the open source device. All economic values are given in U.S. dollars.

3.5. Testing of Device

Since there are no well-established tests for sensory substitution devices, the experimental setup was based on previous experience. Fonseca et al. [47] conducted an experiment with eight blind volunteers and evaluate the results in form of quiz, where participants noted the efficiency in obstacle detection above the waistline. Pereira et al. [10] evaluated their prototype on both blind and sighted participants in five different scenarios to simulate the real-world conditions, including head-, chest-, foot-level obstacles, and stairs. Maidenbaum et al. [11] performed a set of three experiments with 43 participants (38 of them are sighted blindfolded) to evaluate their prototype on basic everyday tasks, including distance estimation, navigation, and obstacle detection. Nau et al. [76] proposed an indoor, portable, standardized course for assessment of visual function that can be used to evaluate obstacle avoidance among people with low or artificial vision.

Summarizing the experience of previous researchers, the set of experiments used to test the devices here consists of indoor and outdoor, structural and natural environment in order to explore the intuitiveness of the developed device and its capabilities in everyday human tasks.

Five sighted blindfolded participants took part in a series of tests, the main purpose of which was to collect the necessary information about adaptation pace, usability, and performance of the developed system. The experiments were conducted in a familiar indoor and outdoor environment for the users.

Participants were assigned to the following nine tasks (Figure 6):

1. Walk along the corridor with an unknown obstacle

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2. Bypass several corners indoors
3. Navigate a staircase
4. Wall following
5. Detect the open door
6. Detect an obstacle outdoors
7. Bypass an obstacle outdoors
8. Avoid collisions with pedestrians
9. Interact with known objects

Figure 6. Testing procedure. **(a)** Walk along the corridor with an unknown obstacle; **(b)** Bypass several corners indoors; **(c)** Walk through the staircase; **(d)** Wall fallowing; **(e)** Detect the open door; **(f)** Detect an obstacle on the street; **(g)** Bypass an obstacle on the street; **(h)** Avoid collisions with pedestrians; **(i)** Interact with known objects.

4. Results and Discussion

All versions of the device were built for less than $24 USD each in readily available purchased components and 3-D printed parts. The economic savings over generally inferior commercial products ranged from 82.2-97.6% for the base system to 76.9-96.9% for the optional module system.

The devices were tested to demonstrate that it has intuitive haptic feedback as outlined above. The device range and accuracy was found to allow a person with a lost eyesight to detect objects with the size of 20 or more cm across with the moving speed of up to 0.5 m/s within the distance range of up to 3 m.

The preliminary testing of the device was determined to be a success based on all the participants being able to complete the nine tasks outlined in the methods section. All participants during the experiments noted the effectiveness of the haptic interface, the intuitiveness of learning and adaptation processes, and the usability of the device. The system produces fast response and allows a person to detect objects that are moving. It naturally complements primary sensory perception of a person and allows one to detect moving and static objects.

The system has several limitations. First, for the developed system, it is necessary to note a narrow scanning angle and a limited response rate, which is expressed in ignoring the danger posed by small and fast-moving objects. Second, the low spatial resolution of the system is also noted. Thus, in the conditions of an outdoor street environment, it was difficult for the experiment participants to track road curbs and determine the change in the level of the road surface. Third, indoors, soft fabrics, such as furniture and soft curtains, as well as indoor plants, can cause problems with distance estimation caused by acoustic waves absorption. In open outdoor areas, determining the distance can be difficult on lawns with high grass and areas with sand. In addition, given the increase in the threshold of sensitivity with age [77], the performed experiments do not cover the diversity of the entire population of people with visual impairments.

Future work is needed for further experimentation to obtain more data and perform a comprehensive analysis of the developed system performance. This will allow designers to utilize achievements in haptic technologies [78] and to improve the efficiency of its tactile feedback, since the alternation of patterns of high-frequency vibrations, low-frequency impulses and beats of different periodicity can significantly expand the range of sensory perception. Similarly, improved sensors could expand range and improved electronics could increase the speed at which objects could be detected. Minor improvements can also be made to the mechanical design to further reduce the size, alter the detector angle to allow for more natural hand movement, and improved customizable design to allow for individual comfort settings as well as aesthetics.

5. Conclusions

The developed low-cost (<$24 USD), open-source navigational support system allows people with the lost vision to solve the primary tasks of navigation, orientation, and obstacle detection (>20 cm stationary and moving up to 0.5 m/s within the distance range of up to 3 m) to ensure their safety and mobility. The devices demonstrated intuitive haptic feedback, which becomes easier to use with short practice. It can be largely digitally manufactured as an independent device or as a complementary part to the available means of sensory augmentation (e.g. a white cane). The device operates in similar distance ranges as most of the observed commercial products, and it can be replicated by a person without high technical qualification. Since the prices for available commercial products vary from $100-800 USD, the cost savings ranged from a minimum of 76% to over 97% (5).

Supplementary Materials: The following are available online at https://youtu.be/FA9r2Y27qvY. Video S1: Low-cost open source ultrasound-sensing based navigational support for visually impaired.

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