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Multi-sensory Feedback-assisted Low-cost Smart Walking Cane Forming a Wearable Assembly for Blind People

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Abstract

Walking along a straight path involves various sensory organs, and the senses are functionalized and harmonized for path navigation. However, visually impaired people not only are unable to find the target path but also face the risk of accidents and injuries. In this study, we propose an affordable wearable cane with the added feature of smart feedback assistance, which can guide people along straight paths. The practical smart cane, which has ultrasonic sensors to detect obstacles, an inertial measurement unit with a gyroscope for path detection, and crucial real-time haptic feedback to provide out-of-line warnings, ensures the user's safety and confidence. Its fabrication using 3D printing creates a compact assembly. This study verified this idea through experimentation and simulation. The results showed that 70% of the deviations were less than 4 ft from the goal. Minimum, average, and maximum deviations of 2, 8, and 20 ft, respectively, are predicted if users attempt to cross a 60 ft street. The idea is that an affordable and innovative walking assistance device based on a smart cane could greatly help many people by keeping them on a straight path, preventing hazards, and allowing them to share social spaces equally.

Keywords: Sensor, Smart, Cane, Haptic, Wearable

1. INTRODUCTION

Movement is an essential process for utilizing environmental space as well as interacting with people and tools. Walking straight without losing direction is a vital way of reaching a destination. Maneuvering to avoid objects is essential for performing housework indoors. Straight walking is one of the most basic human behaviors and involves moving toward goals, avoiding objects, and fulfilling social activities. Walking along a straight path requires the involvement of various sensory organs. When people move, they input visual information, set an optimal route, and take steps accordingly. When an unexpected situation occurs while moving, the visual sensory organs fundamentally recognize obstacles and interference and then reroute. In addition to visual ability, we use other senses, such as touch, hearing, and smell. Irregular noise and smell recognized during movement indicate that there are risk factors in the walking path and avoidance movements must be followed. As such, various senses are functionalized and harmonized in real time to advance travel. However, unpredictable issues arise when the ability to walk cannot be fully utilized due to nature or accidents [1]. If the function of the sensory organs is damaged, a person cannot recognize obstacles or walk straight and thus cannot arrive at the destination accurately. In addition, people face inconvenience and risk of further injuries. According to a report released by the World Health Organization in 2019, at least 2.2 billion people worldwide are visually impaired or blind [2]. Therefore, efforts to compensate for impaired visual abilities must continue.

Engineers have recently researched and developed devices to overcome sensory malfunctions. One study suggested that moving aids for people who are blind can be developed in three phases [3]. The first phase focuses on obstacle detection using a walking cane. Ultrasonic and laser techniques have been used to recognize objects [4,5]. An ultrasonic sensor is used to measure the distance from the obstacle. The data are then sent to the controller for processing, which produces a beep alarm as the output. Because the user must focus on the alarm in the earphones, the system has the disadvantages of blocking real-time conversations, white noise, and dangerous signals. A laser sensor is capable of precise measurements, but if it is pointed at a person who is not an obstacle, it causes social disapproval and controversy over its harmfulness [6]. The second phase involves

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global positioning system (GPS) navigation and wayfinding devices [7]. GPS systems generally have a low accuracy of a few meters; therefore, they cannot recognize small obstacles that can interfere with the blind [8]. Recently, to move along a crosswalk safely, an IoT cane was developed that employs Bluetooth to operate traffic lights and sound signals in the direction of a blind person [9,10]. This advanced application uses wireless communication. The availability of Bluetooth technology varies depending on the version of the mobile terminal and is only used to transmit information to users over short distances. In particular, it requires a pairing process and a connection delay between devices.

According to literature reviews, walking canes are an effective formula for low-cost and facile moving aids [4,6,11-13]. Using a cane, users can check the movement path or recognize obstacles by tapping the floor or rocking left and right at regular frequencies. Canes are universally used because they are inexpensive and easy to use compared to a guide dog or operating surgery for impaired abilities. In addition, the simple structure and light weight of the cane provide users with low loads and excellent mobility. Moreover, the cane provides route information in the fastest and most intuitive manner. However, most people rely on the simple function of a cane as a stick. A smart cane is appropriate for further study because the simple and foldable structure of canes makes it possible to mount small electronic parts that restore the human body sensations. Several smart cane prototypes have been proposed. Nevertheless, few walking canes have assistive functions. One study used three ultrasonic sensors attached to a cane at varying angles, and each ultrasonic sensor measured the distance from objects when walking [6]. However, the idea is only applicable for momentary walking events, and the user remains in a zigzagged walking motion. Advanced vision technologies, such as image sensors or LiDAR, have recently been utilized [14-17]. Image sensors and LiDAR are being developed along with object recognition and artificial intelligence technologies; thus, performance improvements are expected [18]. These sensors, which are core elements of recognition systems, can provide sufficient precision to replace human vision. However, to process visual data, the cost of the microprocessor and storage device is significant, resulting in an increase in the price of smart systems [18,19]. Meanwhile, wearable devices are becoming increasingly popular and have the advantage of keeping the hands free. Wearable formats provide visually impaired people with opportunities to enjoy life, including traveling, exercising, texting, and communicating. Thus, the wearable design can ultimately be used by functionally blind people who use a cane, guide dog, and travel luggage simultaneously [10,17,20]. Although most studies have focused on obstacle detection via multi-ultrasonic sensors, wireless signals, or camera-based vision recognition, none have focused on straight-path detection using a simple and low-cost wearable methodology.

In this paper, we propose an affordable wearable smart cane with the added feature of smart feedback assistance that can guide people with disabilities along a straight path. We prototyped the idea using a microprocessor, which is an efficient module for developing facile and compact measurement systems. The system is inexpensive and easily accessible, and has been actively used to create prototypes of IoT technology ideas [21-23]. The most significant advantage of microprocessors is that they can efficiently operate various sensors and actuators to provide tactile feedback. In addition, sensors allow smart canes to obtain reliable real-time data on changes in walking direction, which enables better straight-line path navigation [24]. A gyroscope is a crucial sensor used to maintain the orientation of a travel stick by detecting the rate of change in angular position over time along the X-, Y-, and Z-axes. Gyroscopes have been used to maintain orientation and stabilize posture in a variety of engineering, medical, and safety applications, including aircraft, spacecraft, robots, and mobile phones [25-27]. They function based on a scientific principle called the gyroscopic effect. This effect can be described as the ability of a rotating body to maintain a stable orientation along its axis of rotation. In the context of motion, a gyroscope can measure or react to motion in multiple directions. Integrating a gyroscope allows the smart cane to accurately recognize movements within 3D space. This allowed us to determine a straight path for walking. Moreover, the use of additive manufacturing facilitates the prototyping of smart canes. A 3D-printed assembly can pack small components into a wearable form and can be simply attached to the cane. The cost of producing and demonstrating the system was effectively reduced.

An inexpensive and innovative walking assistance system developed through design and fabrication processes based on a smart cane that helps visually impaired people to maintain a straight path and share social spaces equally could be extremely helpful. Although several solutions have emerged, portable, affordable, and efficient navigation devices are still lacking. The ideas presented in this paper aim to open a way for sharing and utilizing facile design, prototyping, fabrication, and verification methods.

2. METHODS

2.1 Materials and Tools

The cane (Drive Medical Deluxe Folding) is a 4-section foldable medical-grade aluminum stick. In this study, the cane provides the structural capability for folding and portability, and the lightweight aluminum minimizes user discomfort, even when sensors are added. The cane has a reinforced nylon tip and a wrist strap, which are standards for providing reliability to the user and protecting the device. The belt (AGPtek, police security tactical combat gear belt) is made of durable nylon, making it lightweight and tear-resistant. It can withstand the stress, even when a wearable system package is attached. The electronic housing was constructed using additive manufacturing. 3D printing (flash) is a technology that is being used in small-scale production of various parts, such as the prototype used in this study [28]. This method involves melting or solidifying materials and stacking the cross sections of a structure individually, which allows for individual product design and reduces manufacturing costs by using only the material necessary for the shape of the part [29]. The 3D printing process is discussed in detail in Section 2.5. The Arduino board is powered by a 9 V lithium-ion power source (commercial battery). The inertial measurement unit (IMU) (6 DOF, ITG3200/ ADXL345) has a MEMS structured gyro-sensor on board with a full-scale range of ± 2000°/s and a sensitivity of 14.375 least-significant bit (LSB) per degree per second. The IMU board has two mounting holes for secure attachment to the wearable assembly. A low operating current consumption of 6.5 mA ensures long battery life, and a stabilization time of 50 ms ensures fast use of the smart cane. A microcontroller (Arduino Mini Pro) was connected to a range finder (Ultrasonic Range Finder-LV-MaxSonar-EZ3) and actuator (Mini Vibration Motor for Arduino). Software coding was accomplished using the open-source Arduino Software (IDE). The mechanical design used 3D design software (Inventor, Autodesk Co.). The test was performed in accordance with the relevant guidelines and regulations. Informed consent was obtained from all the subjects. All the methods were performed in accordance with the safety of the users. As the device was worn over clothing and operated while wearing laboratory gloves, it did not touch the subject's skin and did not cause any changes to the body. The participants were not manipulated directly. In addition, no invasive actions were realized, such as drug or blood collection, or eating. No sensitive information was collected or recorded.

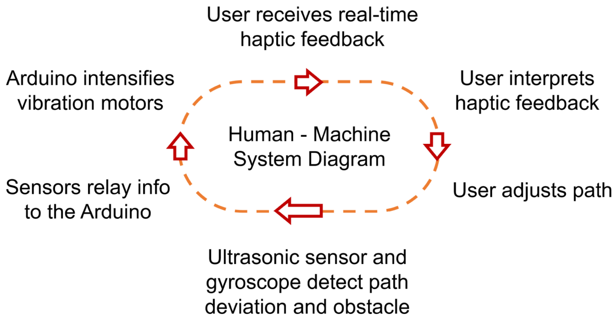

Fig. 1. Conceptual diagram of the human–machine system.

2.2 Conceptual Design

As shown in Fig. 1, the smart cane performs two functions: keeping the user on a straight path, and warning the user of obstacles. The path deviation was analyzed using an electronic gyroscope mounted on the belt. The obstacles were detected using an ultrasonic sensor mounted on the cane. A small microcontroller interprets the signals from the sensors. It warns or corrects the user by activating vibrating motors in the hand (for obstacles) or waist (for path deviation). The motor intensity can vary depending on the degree of deviation. Users who receive haptic feedback in real-time interpret the vibrations in their hands or waist and apply appropriate path adjustments.

2.3 Electrical Design

The electrical hardware, which minimizes cost and signal processing time, consists of the following parts, which can be purchased in the general market and are highly compatible components for constructing a miniaturized form factor. In addition, with the selected components, processing speed and range of detection can be flexibly adjusted.

- Arduino: Arduino is the brain behind the surgery. It records all the information from the sensors and determines whether a straight-path deviation occurs or whether the user is approaching an obstacle. If this occurs, it sends signals to the vibrators on the belt or cane to alert the user.
- Vibrotactors: Small motors placed on the belt and cane. They vibrate to warn the users that the path must be adjusted. The vibrator has an off-center motor to create nonlinear rotational vibrations. The motor has a simple structure and is reliable; therefore, it is used in various mobile devices.
- IMU: The IMU constantly reads the user positions. When the user deviates in either direction, the accelerometer in the IMU records information. The IMU gyroscope helps to eliminate the

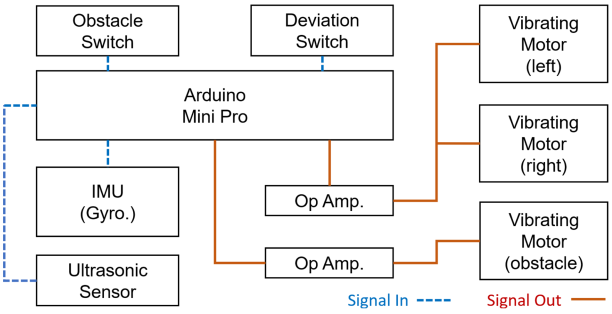

Fig. 2. Electrical components and block diagram.

confounding effect that the user's natural gait adds to the equation.

- Ultrasonic Sensor: An ultrasonic sensor measures the distance to a target object by emitting and receiving ultrasonic sound waves. Thus, an ultrasonic sensor utilizes echolocation to determine whether a user is approaching an obstacle.

The electrical configuration is shown in Fig. 2. The schematic shows the functionality and connectivity between multiple electrical components. A directly connected battery powers the Arduino microprocessor built into the housing system. Using the signal obtained from the IMU, the left and right vibration motors on the waist of the user can be operated separately when the device deviates from a straight path. When the Arduino receives a signal from the ultrasonic sensor that recognizes an obstacle in front, it sends a signal to the vibration motor on the handle of the smart cane.

2.4 Computational Design

Based on instantaneous stimulation, users can walk safely by compensating for walking deviations and avoiding obstacles. As shown in Fig. 3, the straight-path maintenance algorithm of the code has two main feedback categories. The user must wear the cane assembly. The user presses a button for the desired walking-assistance function to supply an electrical current. The corresponding sensor module is then activated, and the step of recognizing the user walking begins in real time. As described in this section, the assembly contains two sensor modules. The user turns the device on while walking. In the first sensor, the alarms are analyzed for walking deviation using gyroscopic sensory feedback. In the second one, obstacle and alarm analyses are performed using ultrasonic sensory feedback. The two feedback algorithms operate in real-time. Haptic alarms are activated on the belt or cane when a walking deviation or obstacle is recognized. The haptic alarms can be simultaneously provided. Users can adjust their walking direction or walk around obstacles based on the haptic warnings. If no haptic warning occurred while walking, the subjects continue walking forward.

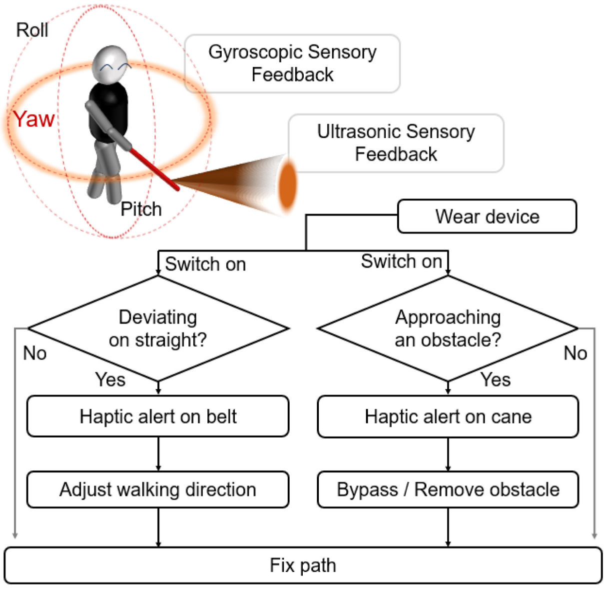

Fig. 3. Straight-path maintenance algorithm.

```
Void loop {
  if (digitalRead(switchOne))              // if user switch the deviation button
     gyroVal = gyroVal + gyroRead          // read gyro-sensor data

  if (gyroVal > 5000)                      // deviating right
    vibroRight                             // turn on vibrating motor
  else if (gyroVal < -5000)                // deviating left
    vibroLeft                              // turn on vibrating motor
  else
    digitalWrite(vibro, LOW)               // keep vibrating off

 if (digitalRead(switchTwo)                // if user switch the obstacle button
     ultraVal = ultraVal + ultraRead       // read ultrasound sensor data
  if (ultraVal > 700)                      // deviating right
    vibroObstacle (ultraVal)               // turn on vibrating motor with
                                              intensity proportional to nearness
  else
    digitalWrite(ultra, LOW)               // keep vibrating off

    Serial.print                           // monitoring data
}
```

Fig. 4. Pseudocode for sensing and vibration.

The pseudocode is shown in Fig. 4. The code for the sensors typically involves reading the sensor and making decisions based on its value. The actuator operates automatically using the input commands determined by the Arduino microprocessor based on the sensor values. The cane uses a sensor module that operates as a combination of a 3-axis gyroscope and a 3-axis accelerometer. To maintain the path, the code recognizes the rotational acceleration based on the z-axis when the user rotates the waist to the left and right, similar to the yaw shown in Fig. 3. The sensor generates a digital value. The change in the value of the IMU determines whether it is a left or right rotation, based on the positive and negative phase shifts. This direction can be indicated independently of the size of the IMU value. The sensor inputs a digital signal until the z-axis rotation is restored. The ultrasonic sensor also generates a digital value and inputs it into the microprocessor. At this time, the digital value varies depending on the obstacle distance. Therefore, the user can recognize the distance of the obstacle placed in front and prepare for an evasive action.

2.5 Printing for Fabrication

The prototyping process consisted of direct preparation of parts of the shielding cases via 3D printing. The 3D printer used was an Adventurer4 (FlashForge). The SolidWorks CAD software was used to design the structures. STL files were converted into sliced layers using FlashPrint software. The filament was made of polylactic acid (PLA, 1.75 mm, FlashForge). PLA is a polymer material used for printing that offers excellent interlayer bonding, which is the ability of recently extruded materials in the print path to bond well with recently printed and cooled materials. Excellent intralayer bonding significantly improves the blending of strands and layers, resulting in a user-compatible smoother surface [29,30]. In the printing setup, the extruder temperature was 225°C, the platform temperature was 55°C, and the printing speed was 50 mm/s. The fill density was set as 30%. The supporting aid option was linear with overhang critical angle of 55° and column diameter of 1.5 mm. Linear support printing requires more filaments but provides a good output quality. Tree-type support printing uses fewer filaments but tends to produce low-quality output at higher heights.

3. RESULTS AND DISCUSSIONS

3.1 Wearable Cane

As shown in Fig. 5 (a), the research processes involve 3D printing to create a wearable smart cane assembly with ultrasonic sensors to detect obstacles, an inertial measurement unit (IMU) with a gyroscope for path detection, and real-time haptic feedback to provide outline path warnings.

Fig. 5 (b) illustrates the principle of path warning. The ultrasonic sensor has an effective range of approximately 14.7 ft at a 15° angle. The sensor emitted ultrasonic waves at 40 Hz and detected the reflected echoes. The speed of ultrasonic waves in air at room temperature is approximately 1115 ft/s; therefore, dividing by the time it takes for the ultrasonic echo to return gives the distance between the sensor and the object, which is distance = (Vultra × $T_{timedelay}$) / 2. Vibrations are generated when an object in front is detected, and a vibration motor that provides haptic feedback is fixed just below the handle of the cane. The gyroscopic sensor detected deviations during walking. When the belt was worn, a haptic feedback vibration motor was installed on the left and right sides of the user's waist. These two vibration stimuli use information from the gyroscope to provide vibration stimuli when the user deviates from a straight walking path.

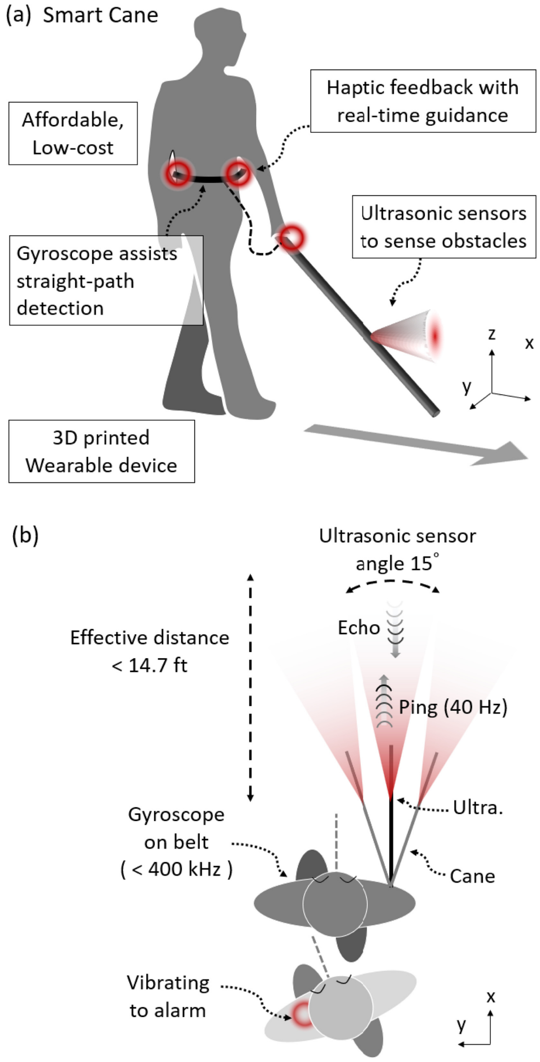

Fig. 5. Principles of assistive warning while walking. (a) Affordable wearable smart cane with added smart feedback assistance. (b) Warning system using sensor and actuator.

Fig. 6 shows the prototype product and its assembly using 3D printing and mechanical design. Fig. 6 (a) shows a conceptual smart cane with an ultrasonic sensor attached to it. The primary control system of the wearable belt consists of a gyroscope sensor, microprocessor, battery, and Arduino mainboard fixed with a 3D-printed box. The vibrating box was securely connected to a

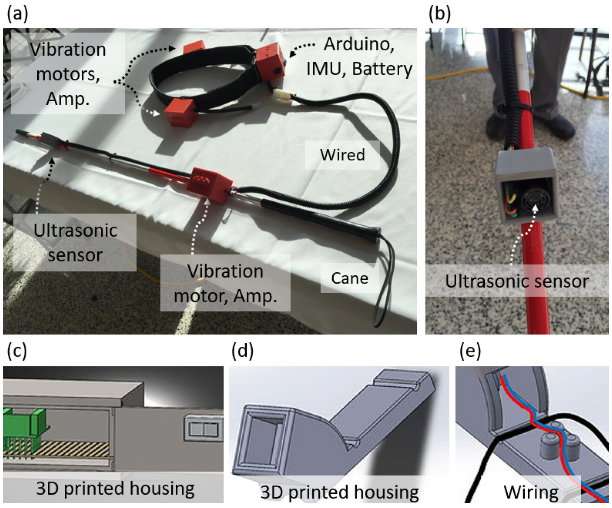

Fig. 6. Prototyping (a) Assembly of the cane (b) Ultrasonic sensor mounted on the cane (c) 3D design for housing (d) 3D designed sensor housing (e) 3D designed electrical connection.

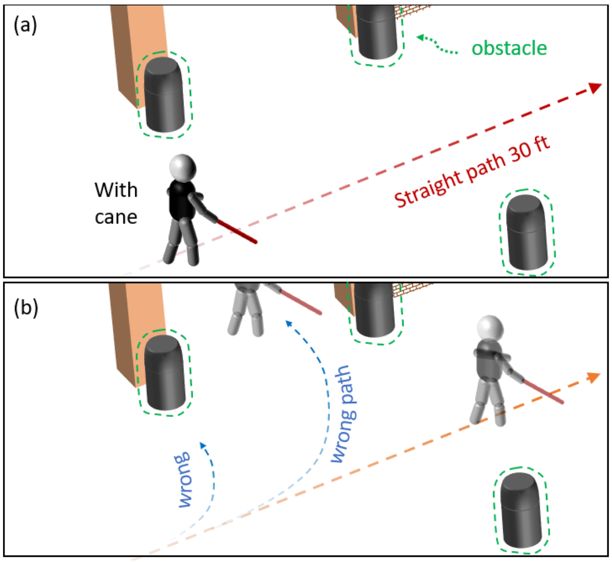

Fig. 7. Test schematic (a) Evaluation through straight path. (b) Walking on a straight path and deviation.

wearable belt within a corrugated polymeric shield. Fig. 6 (b) shows the ultrasonic sensor attached to the cane. The ultrasonic sensor has an intentionally tilted angle that allows it to point forward when the user taps the stick. When walking using the smart cane, the ultrasonic sensor is placed at a 40° angle from the cane. This angle was established through geometric analysis using computer-aided design for testers with a height of 5.5 to 5.9 ft. Fig. 6 (c) shows the system housing used to functionalize the wearable belt. A sliding door is used to achieve light weight. A single-sided sliding open/closed door is available for quick maintenance, such as battery replacement and hardware debugging. It is equipped with toggle power buttons that instruct the user to begin or reset the sensors. The toggle switch that turns the main power source on and off is on the outside. This button has a raised volume that allows the user to actuate it without visual confirmation. As shown in Figs. 6 (d) and (e), the 3D housing design provides an ultrasonic sensor that can be securely attached, and the electric cables are extended to the back of the housing and immediately protected by a polymer shield. Shielding and customized structures can protect electric cables from damage during user scenarios, such as placing and swinging the cane.

3.2 Indoor Testing

Tests with ten blindfolded students were carried out to determine the effectiveness of the proposed smart cane, as shown in Fig. 7 (a). Two tests were performed with the participants. In the first, to determine how well the straight-path detection functioned, the participants walked 30 ft and it was ascertained how far off the path they ended up. In the second test, the participants had to avoid four obstacles placed in their path, thus allowing to test the ultrasonic sensor and reliability of the feedback. The users were blindfolded and evaluated in a controlled indoor environment to ensure safety. Each test was performed for the analysis.

Fig. 7 (b) shows a schematic of the results. In the experiment involving walking on a straight path, the test quantitatively evaluated the deviation from the invisible line. Additionally, the idea examined the case of going off a straight path and going on a different path by utilizing an open space on the left. In the obstacle detection test, two cylindrical trashcans were set up on the left and two on the right, so that the user could encounter obstacles while walking. The obstacles were positioned at different distances from the path but could be directed towards it by the user swiping the cane left and right. There was a sidewall behind the obstacle, but this was an unintended structure; therefore, it was not included in the number of times an obstacle was encountered. If part of the user's body touched an obstacle, it was determined that the obstacle was not recognized.

3.3 Evaluation

In Fig. 8 (a), the analysis reveals the number of deviations within the 30 ft walking plan. Among the participants, 70% made deviations of less than 4 ft, two within 1 ft, two within 2 ft, two within 3 ft, and one within 4 ft. The results of this experiment

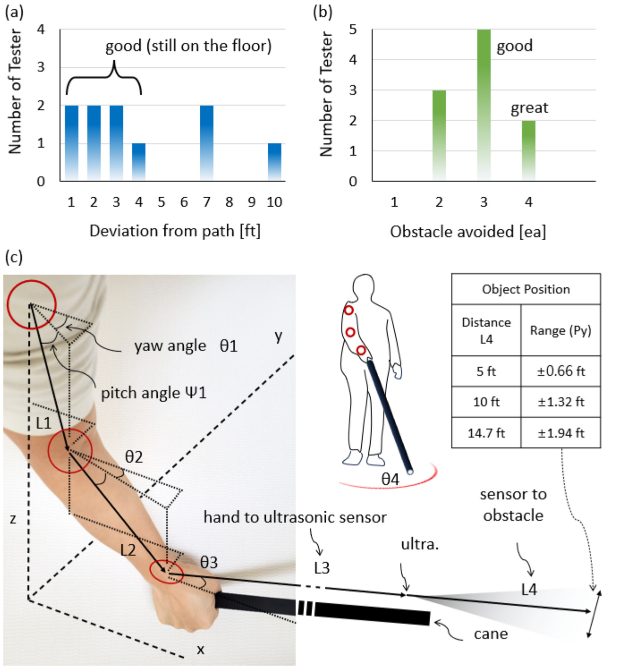

Fig. 8. Result and analysis (a) Number of deviations within 30 ft during walking. (b) Number of obstacles avoided by users. (c) Position estimation using links and joints.

showed that deviations within 4 ft meant that the participants were still in the testing space, and the feedback system allowed users to refine the straight path. The participants precisely corrected their paths using motor alarms and performed high-quality straight walking. In contrast, two participants deviated by 7 ft, and one wandered 10 ft away from the target path. In all attempts, the motor alarms worked adequately. The reasons for the errors in path correction are as follows: First, when the user's body is rotated around the z-axis to correct the path, an irregular path correction occurs if the body rotation angle per alarm is too large. If the body moves rapidly, the tolerance of each rotation increases, and the path-correction process creates irregular zigzag movements that gradually deviate from the path. Therefore, the motor warning operates at a constant current value independent of the value of the gyroscope. Hence, if the same rotation amount of approximately +/- 5° is applied, the exact path can be found as a result of the converging zigzag movement. Second, errors can occur when there is a lack of sense of vibration. The participant with a deviation of 10 ft had difficulty determining whether the vibration generated by the motor was to the left or right. The vibration of the motor was transmitted to the waist of the user through the assembled belt. In this process, the sense of the person's waist, thickness and structure of the clothing, and accessories can create an effect that further disperses or interferes with the vibration. The users can continuously scan by changing the vibration intensity. However, the sensitivity of each individual and variables such as clothing and rotation amount result in the need for proper training of the user.

Fig. 8 (b) shows the results of obstacle avoidance during walking. Two participants successfully recognized and avoided all four obstacles. Five subjects avoided three obstacles, and three avoided two obstacles. None of the users avoided one or zero obstacles. Because the alarm generated by the ultrasonic sensor changes the intensity of the motor according to the distance, the user can converge to the exact direction of the obstacle through continuous scanning of the cane and alarm intensity. Because the ultrasonic sensor has a frequency of 40 Hz and a repeat echo acquisition capability of 25 ms, forward monitoring precision can be improved through rapid scanning by increasing the arm swing speed or reducing the angle without hardware limitations. Fig. 8 (c) illustrates obstacle recognition using Cartesian coordinates [25]. The sensor system of the smart cane provides the distance between the ultrasonic sensor module and obstacle; however, Cartesian data processing using the structure of the arm can provide the user with precise obstacle location information. The idea proposed in this study is to fix the pitch and actively search for objects placed in the x-y plane by performing yaw rotation. The cane's yaw rotation angle (θ4), which determines the direction of the ultrasonic sensor, is controlled by the user's arm links and joints. The shoulders, elbows, and wrists are constrained to rotate. The angles of each joint are acquired through user scenes, and these angles can provide information about the yaw, pitch, and roll. The yaw and pitch angles made at the shoulder are θ1 and Ψ1, and those made at the elbow are θ2 and Ψ2, respectively. The wrist fixes the pitch rotation and creates θ3. The three axes of the Cartesian coordinates are x, y, and z, where the x-axis position of the object is Px, y-axis position is Py, and z-axis position is Pz. The links are L1, L2, and L3 from the shoulder, and the cane is L4. The following formulas calculate each Cartesian equation:

$$Px = L1 \cos\Psi1 \cos\theta1 + L2 \cos\Psi2 \cos\theta2 + (L3 + L4) \cos\theta3$$

$$Py = L1 \cos\Psi1 \sin\theta1 + L2 \cos\Psi2 \sin\theta2 + (L3 + L4) \sin\theta3$$

$$Pz = L1 \sin\Psi1 + L2 \sin\Psi2 + (L3 + L4) \sin\Psi3$$

$$\theta4 = \theta1 + \theta2 + \theta3$$

Because the field of view of the ultrasonic sensor in the x-y plane is approximately 15°, the Py range for recognizing obstacles in front of the ultrasonic sensor is 1.32 ft at 5 ft, 2.64 ft at 10 ft, and 3.87 ft at 14.7 ft. In the test, the effective field of view created

Table 1. Individual test results and opinions

Tester No.	Deviation in 30 ft	Obstacles avoided	Vibration repetition	Left/Right distinction
1	2	3	More	effective
2	3	3	Less	effective
3	10	4	effective	ineffective
4	7	2	More	effective
5	7	4	effective	effective
6	1	2	effective	effective
7	2	3	More	effective
8	1	4	Less	effective
9	3	4	effective	effective
10	4	3	effective	effective
Average	4	3.1	effective	effective

by swinging the cane left and right by approximately 70° to 90° is approximately 85° to 105°. This angle is a valid range for detecting dangerous objects in front of the user.

As presented in Table 1, after completing the test, we asked the users whether they wanted more or less vibration. Sensibility ergonomics is an engineering approach that realizes images or emotions as desired in specific product designs. Vibration intensity and repeatability can be adjusted through sensibility ergonomics based on the deviation and obstacle avoidance abilities. Approximately 60% of the participants responded that they were satisfied with the vibration alarm. The responses of participant 4 were significant. He obtained a negative result of a 7 ft deviation and avoided two obstacles, and therefore responded that he wanted more vibrations. However, there was no correlation between the experimental and survey results for most of the participants. Participant 3 had a significant deviation but responded that the vibration was effective. In contrast, participants 7 and 8 successfully achieved a deviation of 1 ft and avoided four obstacles, but responded that the vibration should be improved further. In addition, participants 7 and 9 also succeeded in deviating and evading by 2 and 3 ft, and 3 and 4 ft, respectively, but expressed random claims that they wanted more vibration or that it was effective. Therefore, if this smart cane is to be distributed for personal use in the future, it should be able to customize the vibration and sensor sensitivity. In addition, we asked the participants whether dual-motor vibration was appropriate for providing a deviation alarm. The concept of dual motors was considered effective by 90% of the participants. Participant 3, who had the most significant deviation of 10 ft, stated that dual vibration was ineffective. Participant 3 was the only one who deviated significantly from the path and lost sight of the target. In contrast, the other nine participants had deviations of less than 7 ft and could steer according to the vibration. Therefore, the alarm is effective as long as the left and right vibrations can be distinguished. However, if the user cannot determine the vibrations, directional guidance does not work. For the variables that make it difficult to distinguish the vibrations, please refer to Fig. 8 (a).

3.4 Outdoor Simulation

To reflect the willingness for future real-world testing and ensure the practical relevance of the study, preliminary graphical simulations were performed to test actual streets with people present. Fig. 9 (a) shows a 60 ft-wide crosswalk captured from an online map (Street View, Google). Based on the indoor test results, if the user wants to walk straight on the crosswalk, the prediction reveals minimum, average, and maximum deviations of 2, 8, and 20 ft, respectively. Approximately 70% of the users have deviations within approximately 2–8 ft, as indicated by the yellow and orange lines. Considering the repeated guidelines for pedestrians and stop lines for cars, this appears safe for pedestrians. However, approximately 30% of users may deviate from the pedestrian guidance lines. Although guidance based on single data using a gyroscope provides these predictions, walking can be improved if ultrasonic sensors work together. By recognizing cars stopped at the stop lines drawn on the left and right sides of the pedestrian as obstacles, the system suggests improved directionality to the pedestrian. Thus, errors are reduced.

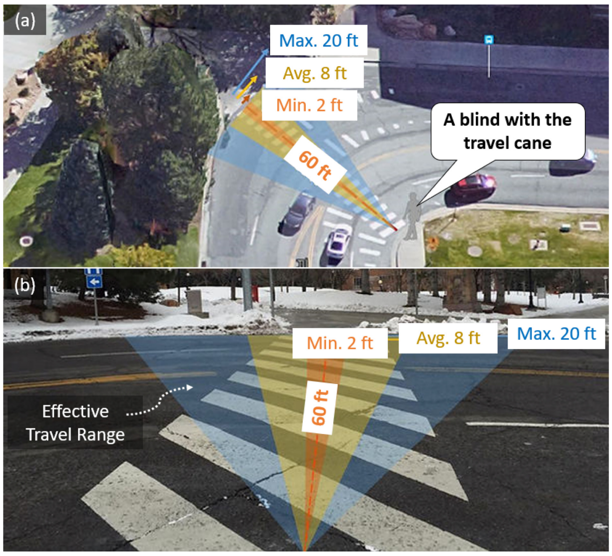

Fig. 9. Outdoor simulation (a) Skyview simulation using outdoor crosswalks. (b) Street view of the prediction.

3.5 Future Improvements

In this section, we review the limitations of this study and the improvements that can be made by addressing its limitations. First, a feasibility test through prototyping provided valuable insights into the effectiveness of the smart cane, and additional testing enhanced the robustness and reliability of the results. However, because only ten blindfolded subjects participated in the experiment, it is difficult to support the claim that the proposed solution is statistically valid and generalizable. Each blinded participant can repeat the experiment multiple times. This allows for a more comprehensive evaluation of the cane performance by calculating the mean, standard deviation, and least-squares error metrics. Establishing a statistical analysis based on statistical metrics (e.g., standard deviation and confidence interval) can help readers better understand the results. Second, the scope of obstacle recognition should be expanded from a single x-y plane to three-dimensional recognition. The space in which a person walks should be analyzed using a three-axis coordinate system because obstacles and hazards exist in three dimensions. For example, a hanging panel can threaten the user’s upper body or a staircase in front can cause the user to fall. Multiple ultrasonic sensors can be utilized to enhance the performance of smart canes, and high-performance sensors, such as the time-of-flight (TOF) technology used in camera technology, can be used to improve resolution, fast detection, and 3D recognition.

4. CONCLUSIONS

With an aging world population, and considering the gap between rich and poor, as well as between developed and underdeveloped regions, there is an urgent need to help people overcome their impaired vision. In this study, we developed a smart walking cane for the visually impaired. First, it involves easy-to-use and low-cost components and modules. The experimental approach utilizes a simple data-processing system using an Arduino microprocessor. This design attaches an ultrasonic sensor to the walking cane and monitors the front of the user. Using an IMU module with a gyroscope, the cane monitors the user's deviation from a straight path. The cane is designed as a wearable assembly that can utilize not only the sensory organs of the hand but also redundant sensory organs such as the waist of the human body. Consequently, a compact wearable prototype was successfully fabricated using a 3D-printed case and belt. The motors installed on the left and right sides of the belt provided vibration alarms based on the deviation of the input from the IMU. These tests demonstrated the potential for developing higher functions. Therefore, verification was conducted through indoor user experiments. The system's multi-feedback enabled path improvement, multiple users corrected their paths in real time, and their errors converged. The cane can be easily upgraded with higher precision in both software and hardware, allowing it to scan a wider range of spaces to meet the needs of each user and set the sensor sensitivity and alarm intensity to suit user preferences.

Through proper prototyping and evaluation of open possibilities, the cane will help visually impaired people navigate much better than when using a conventional cane alone. This cost-effective and simple system configuration provided users with high accessibility. If mass-produced at a low cost, this idea is expected to contribute to solving the inconveniences faced by visually impaired people. In addition, the results of this study are expected to contribute to the field of wearable devices as well as to developing facile manufacturing techniques.

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