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FutureBody-Finger

A Novel Alternative Aid for Visually Impaired Persons

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***Abstract*—We have developed a sensory substitution device (SSD), called FutureBody-Finger (FB-Finger) based on a “smart” mechanism with an ecological interface. The primary aim of FB-Finger is to enable visually impaired persons to “recognize” their surrounding environment, specifically in terms of distance. FB-Finger comprises a position-sensitive device (PSD) sensor unit and a small actuator unit and is used to sense the distance as follows: (1) The distance between a (visually impaired) user and an object is measured via ultrasonic waves or infrared rays radiated from the PSD sensor unit; (2) Information on the measured distance is transformed in the actuator unit into haptic stimulation (“somatosensory stimulation”) and then sent to a servo motor incorporated in the actuator unit; and (3) A lever connected to the servo motor catches the stimulation and creates angular motions to convey the information to the user’s finger. In order to afford the device simple use and portability, FB-Finger was designed with a shape such that the forefinger skin/joints receive somatosensory stimulation. In this paper, we outline the concept underlying FB-Finger, describe its underlying mechanism, and report on two psychological experiments conducted. The results of the experiments show that FB-Finger estimates the distance between two objects (i.e., the user and an object) more accurately, and the somatosensory interface enclosed in the device performs better, than commercially available SSDs. On the basis of these findings, we also discuss the effectiveness, possible future improvements, and applicability of FB-Finger to electric travel aids and other assistive aids.**

Keywords-haptic interface; somatic sensation; ecological interface; assistive technology; electric travel aid.

I. INTRODUCTION

A. Purpose

In general, human beings are thought to obtain information via visual modality, but it is natural that nonvisual modalities also provide people with a significant amount of information. Thus, it is important to shed some light on the role of nonvisual modalities in exploring the surroundings. On the basis of the philosophy and psychology associated with human perception and behaviors, we hypothesize that people are able to subjectively have an “extended body” experience (hereafter referred to as “FutureBody”) that endows them with a sense of effectivity in their surroundings if a device functions as a part of their bodies to enable them to recognize an unfamiliar environment by using that device. We have been working on the development of a device that proves our hypothesis. In particular, our research has been focused on developing a new type of sensory substitution device (SSD) for visually impaired persons to enable such persons to enhance the quality of their lives in terms of utilizing their nonvisual modalities. This paper is an extended version of a paper we presented at AMBIENT2012 [1]. In this extended version, we explain the key concept underlying the FutureBody device, give an outline of our developed device, FutureBody-Finger (hereafter referred to as FB-Finger), describe its hardware configuration, and discuss its efficiency. Finally, we present the latest improvements to FB-Finger (FB-Finger2). However, before delving into those areas, we give a general overview of previous and current aid devices for the visually impaired.

B. Assistive devices for the visually impaired

Devices called sensory substitution devices (SSDs) and electric travel aids (ETAs) have been developed in both academic and industry fields [2-9]. SSDs and ETAs [10, 11] are intended to assist the visually impaired with their activities, such as exploring their surroundings and locomotion. To ensure the safety of these activities, these devices have sensor(s) installed that detect a user’s location, the direction in which the user is moving, and the distance between himself/herself and nearby objects.

SSDs and ETAs obtain information about the surroundings via two major methods. In the first method, a small camera is used to capture images that are then analyzed, and the results of the analysis output to an electro-tactile display or vibration display. OPTACON [12, 13] adopted this method to help the visually impaired read printed letters, and the Forehead Retina System [14, 15] utilizes it to assist users with search of their surroundings. The second method utilizes supersonic wave sensors, which makes it suitable for measuring the distance between a visually impaired person and an object. Products equipped with supersonic wave sensors include Sonicguide [16-18], Miniguide [4], and Palmsonar [6].

SSDs and ETAs are categorized in terms of their output feedback interface as either "auditory" or "haptic." Auditory type devices transform spatial information into audible sound. Sonicguide, for example, measures the distance between an object and a user with ultrasonic waves, converts the data into sound, and conveys the sound to the user. This type of device typically emits a low-pitched sound when an object is distant from the user and an increasingly higher-pitched sound as the object approaches.

Haptic type devices convert distance information into mechanical vibration or electrical-tactile stimulation and convey it to the skin (haptic sense). The intensity/frequency of the mechanical vibration varies according to distance: it increases when a user approaches an object.

However, in order for users to handle such devices, a number of problems need to be solved. Users are required to be trained to effectively use their cognitive inference and memory to comprehend what a stimulus means; that is, how much distance a certain stimulus equates to. To make full use of a device equipped with an interface that outputs the data in the form of sound pitch or vibration, visually impaired adults and children must use the device repeatedly to become expert users. Thus, visually impaired persons have to learn to associate a specific pitch/vibration with a corresponding distance. Such a practice has to be carried out because an arbitrary frequency or an arbitrary intensity from a stimulus is by itself a meaningless signal. Success with associative learning depends on cognitive abilities including inference and memory capabilities. Cognitive abilities take on the leading role in processes where users interpret a pitch/vibration signal correctly, understand the meaning of such a stimulation, and associate it with the distance to an object. This problem applies to the visually impaired, whether congenital or adventitious. If they hope to master one of these devices completely, they have to improve their cognitive abilities; otherwise, training will take a long time, or they will have to give up on actually mastering the device. Furthermore, visually impaired children are unlikely to develop enough high-level cognitive processing abilities, and adventitious visually impaired persons may have more difficulty discriminating pitches of sound and the intensity/frequency of vibration than congenitally visually impaired persons. To enable visually impaired users to receive spatial information more "intuitively" (directly), we developed our device, FB-Finger, with a novel haptic interface.

II. OUTLINE OF FUTUREBODY DEVICE: "SMART" MECHANISM WITH ECOLOGICAL INTERFACE

A. *Key concept underlying FutureBody*

The key concept underlying FB-Finger is adoption of a "smart" mechanism. As suggested by Runeson [19], we define a "smart" mechanism as a mechanism that directly registers complex variables. The operation of a polar planimeter can be used to give an indication of how this "smart" mechanism operates. A polar planimeter is a tool that is used to measure the area of irregular shapes, which necessitates calculation of complex variables. A representative polar planimeter is shown in Figure 1. When a user moves the tracer arm, the attached measuring wheel carefully traces the outline with the index to calculate the area (a complex variable) automatically. The length and angle measured by the polar planimeter are directly proportional to the area. The device is sufficiently simple to use such that those who have no knowledge of the calculations, e.g., summing up small pieces of a figure, can easily determine the area. This "smart" mechanism does not require any computational skills, higher cognitive inference ability, or excellent memory capability.

Extending the discussion of smart mechanism to human perception and performance, we assume that the human body operates in a manner similar to the polar planimeter. The polar planimeter uses a tracer arm with an index to register the summation of the area; analogously, the human body registers information on the surroundings by moving legs, arms, fingers, and joints and by stimulating their bones and muscles (called somatosensory stimulation). Whether they are conscious or unconscious, people are always exposed to such somatosensory stimulations from birth. To directly and intuitively register spatial information for surroundings, humans need to develop somatic sensations that underlie a person's higher cognition and behavioral regulatory systems.

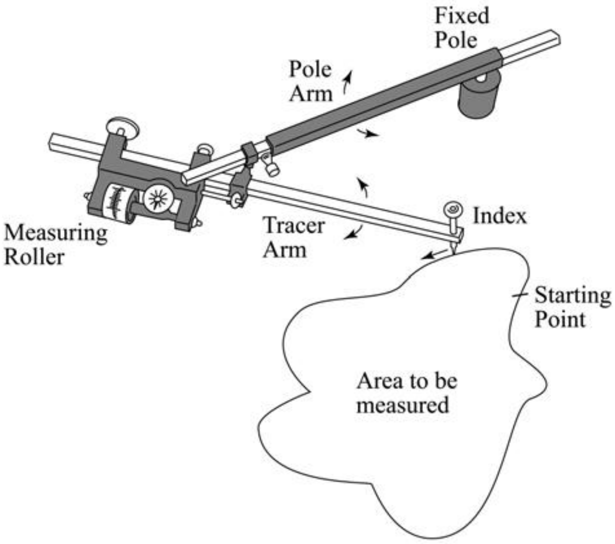

Figure 1. Polar planimeter as a tool for measuring the dimensions of irregular shapes.

Following this assumption, somatosensory stimulation plays an important role in devices that convey information to users directly or intuitively. Thus, we hypothesize that using a somatosensory/haptic interface would enable us to solve the problems outlined in the previous section.

Further, a smart mechanism is required to be equipped with an ecological interface. Here, the term “ecological” originates from “Ecological Psychology” [20] — a subfield of psychology aimed at revealing the human-environment interrelationship from the viewpoint of human’s perception and behavior in the environment. An ecological interface is designed to “reflect” the surroundings, in which information is directly and perceptually available to the persons who use it [21]. Design of ecological interfaces is mainly focused on interfaces for large and complex systems, such as power plants and medical equipment in order to avoid human errors. In this paper, we extend the discussion of ecological interface design to SSDs (or ETAs). The ecological interface of the device functions as a part of the user’s body so that they feel as if their bodies are extended by using it. Furthermore, they are directly exploring and connected to the surroundings so they are able to take effective actions with the interface. An example of a tool with an ecological interface is a pen. When we write letters with a pen, we feel the texture of the paper surface in which the pen is in contact. There are no touch receptors on top of a pen, but the skin of the hand holding the pen has a sense of touch. This sense of touch extends from the skin, through the hand, to the top of the pen. The shape of the pen is such that it is easy to hold with the fingers to help its users easily feel the smooth texture of the paper surface. This can be termed an “incarnation,” as argued by Merleau-Ponty [22]. On the basis of the above arguments, FutureBody should satisfy two requirements. First, it must operate as a smart mechanism with which users can directly or intuitively register spatial information without higher cognitive abilities. Second, it should be equipped with an ecological interface by which the device can function as a part of the bodies of users, and consequently allow users to have a sense of extending their bodies.

B. *Preliminary version of FutureBody device (CyARM) and its mechanism*

Our first step in the development of FutureBody was CyARM [23, 24]. CyARM is characterized by its “smart” user interface. Users do not need calculations, inference, or higher-level cognitive processing to determine the distance between them and an object, whether or not it is moving. Figure 2 depicts the structural diagram of CyARM. The strength of the device’s wire tension enables users to specify distance as well as direction. Connected to the user by a wire, CyARM measures the distance between the user and an object. CyARM emits ultrasonic waves, spotting an object and measuring the distance between the user and the object. At the same time, it also controls the tension of the wire connecting the device to the user. The wire’s tensile strength is directly proportional to this distance. When an object is a short distance away, CyARM pulls the wire tightly, and the user understands that the object can be reached by bending the arm. When the object is far from the user, CyARM slackens the wire, indicating to the user that the object is not within reach. The user can thus explore his/her surroundings with the device.

Ultrasonic sensors measure the distance between the user and an object, and CyARM’s motor slackens or tightens the wire in accordance with the measured distance. The wire is rewound to the initial default position, and the rewinding tension is regulated in accordance with the measured distance. High tension signifies a short distance, while low tension signifies a longer distance. CyARM uses a somatosensory stimulation user interface such that users can obtain distance from themselves to an object via bending or extending their arms.

The basic mechanism underlying CyARM is as follows: The motor is Maxon GP16 (4.5W) with a 29:1 gear head and magnetic rotary encoder; the motor driver is iXs iMDs03-CL; the MPU is Renesas H8/3664, and the ultrasonic frequency used is 38 kHz.

The results of our previous studies indicated that CyARM is feasible for visually impaired persons. Psychological experiments conducted in which CyARM was used to estimate the distance to an object showed high accuracy and correlation to the actual distance. In addition, another psychological experiment also found that CyARM is effective in perceiving the shapes of objects [25, 26]. However, CyARM is too large to carry for daily use and its mechanism inhibits the user’s arm and trunk movement. In addition, its ultrasonic sensor has only low resolution for measurement of distance. Thus, CyARM is impractical for daily use. In order to overcome those usability and portability issues, we developed a novel “FutureBody” device called FutureBody-Finger (FB-Finger).

III. FUTUREBODY-FINGER: BASIC MECHANISM AND HARDWARE CONFIGURATION

FB-Finger was developed to enable users to recognize the direction of, and distance from, an object. Using it, people do not require higher cognitive abilities such as mathematical calculations, inference, and excellent memory to recognize the distance to an object. The device has been verified to solve some of the usability problems discussed in

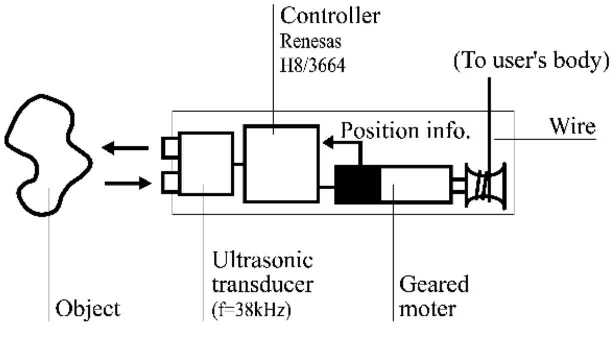

Figure 2. Structural diagram of the prototype CyARM, developed by us.

the previous sections.

The hardware architecture of the prototype FB-Finger is shown in Figure 3. The developed FB-Finger consists of three functional blocks: a controller, a sensor, and actuator units, all of which are connected to a common communication channel. Each unit has a microcontroller (MCU, Cypress CY8C21123).

The sensor unit acquires information about the environment via an adequate sensor device, and converts it to a digital value. We developed four types of sensor units with different sensor devices. The first and the second equip a position-sensitive device (PSD)-type distance sensor that radiates infrared rays toward an object; it detects the reflected position of the received rays using a PSD that implements a trigonometric distance measurement technique. We employed two different PSD devices: GP2Y0A21YK and GP2Y0A02YK by Sharp Inc. They have different distance measurement ranges: 100 mm – 800 mm for GP2Y0A21YK, and 200 mm – 1500 mm for GP2Y0A02YK. They output voltage signals corresponding to the measured distances. The supply voltage used is 5 V, and their physical dimensions are 30 mm (W), 13 mm (H), 14 mm (D) and 30 mm (W), 13 mm (H), 22 mm (D), respectively. The microcontroller is installed on the sensor unit, and calculates the distance from FB-Finger to an object; with an adequate conversion equation for each PSD sensor.

The third sensor unit equips the ultrasonic distance sensor of PING by Parallax Inc. It measures the distance to the target object in the range 20 mm – 30 mm, and has physical dimensions 22 mm (W), 46 mm (H), and 16 mm (D). It outputs a pulse with a modulated signal according to the measured distance. The microcontroller installed on the sensor unit converts the distance from FB-Finger to the object.

The fourth sensor unit equips the light sensor to measure the intensity of the incoming light, with lens for focusing. It measures luminance intensity at the narrow point on the surface of the target object.

The microcontroller installed in each sensor unit converts the sensor signal to the “distance” information in the same signal format. This enables the system to easily exchange the sensor unit with the same controller unit and actuator unit. In other words, the user can exchange the sensor unit for suitable applications with the one for FB-Finger body with the controller unit and the actuator unit. We here emphasize that the user can select a type of sensor unit according to the purpose of use. This is an important advantage of FB-Finger. We employ a 2.5 mm stereo plug and jack for physical connection between the sensor unit and the FB-Finger body, including the controller unit and the actuator unit. The stereo plug and jack provide the power, the ground, and the signal terminals.

The user can also apply the adequate distance sensor unit for the purpose based on its characteristics. For example, the ultrasonic distance sensor can steadily measure the distance to the object regardless of the material, while the infrared reflection used in the PSD sensor tends to be weak for black objects because of light absorption. On the other hand, the PSD sensor can measure the distance beyond a transparent wall, which is impossible for an ultrasonic sensor. In terms of the distance range available, the ultrasonic distance sensor can be applied to long distances, such as 3 m compared with the PSD sensor. In terms of physical size of the distance sensor devices, the ultrasonic distance sensor tends to be larger than the PSD device for the physical wavelength of the ultrasonic waves.

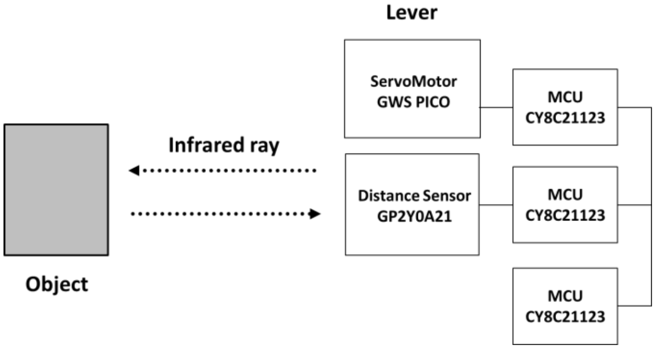

Figure 3. Block diagram of FB-Finger, developed by us, with infrared ray sensor.

The actuator unit has a servo motor equipped with a 55-mm-long lever to form a one degree-of-freedom (1-DOF) link. The microcontroller on the actuator unit controls the servo motor according to the angular information received.

The controller unit periodically requests distance information from the sensor unit, converts the measured distance to angular information, and transmits it to the actuator unit; this chain of operations forms the sensor-actuator system. The angle of the link increases when the distance between FB-Finger and the object decreases (i.e., when the object is approaching), whereas it decreases when the distance increases.

Figure 4 illustrates the method by which FB-Finger is operated. A user holds FB-Finger and places his/her forefinger on the link. The finger bends or extends depending on the link’s angular motion. The angle changes from zero to 70 degrees in correspondence with the metric distances between the user and an object. The extent that the user bends his/her forefinger is directly associated with the link movements, such that a finger motion allows a user to “directly,” and “intuitively” perceive the distance to an object. In this sense, FB-Finger has a somatosensory (haptic) interface that is ecologically designed.

The hardware specifications of the prototype FB-Finger are as follows: weight = 60 g; height = 75 mm; width = 45 mm; and depth = 35 mm. The body and the lever are composed of aluminum. The measurable distance ranges from 300 mm to 1400 mm for the PSD-short range sensor, and 1000 mm to 2800 mm for the PSD-long range sensor as the link angle changes from 70 to zero degrees in both sensors. The distance-angle coefficients are 7 deg/110 mm for the PSD-short range sensor and 7 deg/180 mm for the PSD-long range sensor. The output of the PSD is converted by an analog-to-digital converter, and then transformed to the angle of the lever, which is controlled by the width of the control pulse. The theoretical minimum resolution for the distance measurement is approximately 1 mm.

IV. PSYCHOLOGICAL EXPERIMENT 1: ACCURACY OF ESTIMATED DISTANCE

A. *Purpose*

To demonstrate that FB-Finger enables users to perceive the distance between them and an object more accurately than commercially available products, we performed a psychological experiment as follows.

B. *Method*

1) Participants: 16 persons, visually impaired and sighted, participated in the experiment. Eight visually impaired adults, four congenitally and four adventitiously, participated in the visually impaired group. Their ages were between 28 and 57 years (mean = 43.0 years). Eight sighted adults with ages in the range 20 to 22 years (mean = 20.8 years), participated in the sighted group.

2) Distance Range: Two separate FB-Finger devices were used in order to test for a short range stimuli set (“Short Range”) and a long range stimuli set (“Long Range”). The device designated to test for Short Range was equipped with a short distance sensor whereas the other was equipped with a long distance sensor.

3) Object for Stimuli: A piece of cardboard adhered to a whiteboard (1.6 m × 1.0 m × 0.02 m) was used as the standard stimulus and the test stimuli. We used a standard stimulus and four test stimuli in the Short Range and five test stimuli in the Long Range scenarios.

4) Stimuli presentation: In the Short Range stimuli set, the standard stimulus was presented at a distance of 0.4 m from a device affixed to a table. One test stimulus was presented at each of four positions, specifically, 0.4, 0.6, 0.8, and 1.0 m. In the Long Range stimuli set, the standard stimulus was presented at a distance of 1.0 m in the same manner as the Short Range standard stimuli set. One test stimulus was presented at each of five positions, specifically, 1.0, 1.4, 1.8, 2.2, and 2.6 m.

5) Device Conditions: Three types of SSDs (FB-Finger, Vibratory device, and Sonar device) were used as a within-subject factor. Participants were asked to estimate the distance to the stimuli using each SSD in turn. The Vibratory and Sonar devices used are commercially available ETAs. The Vibratory device (70 mm × 40 mm × 25 mm) was equipped with a haptic interface that transformed measured distances into vibration signals. The Sonar device (60 mm × 35 mm × 15 mm) transformed measured distances into audible sounds (i.e., sounds with a specific pitch). Both devices use ultrasonic waves to determine the distance to an object.

6) Procedure: Figure 5 shows the experimental setup. In each trial, participants were asked to use an SSD to detect the distance to a stimulus that was presented for 3 s. Initially, the standard stimulus was presented, after which one of the test stimuli was randomly presented at a certain distance in each distance range stimuli set.

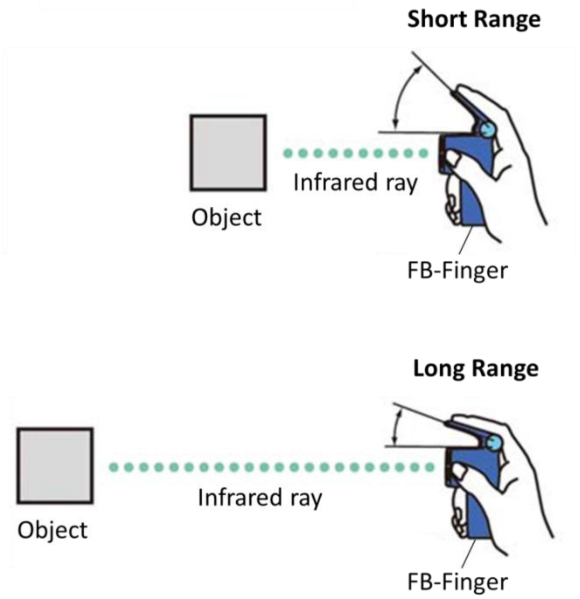

Figure 4. Illustrations showing how to operate FB-Finger with PSD-short range sensor (upper panel) and with PSD-long range sensor (lower panel).

The magnitude estimation method was used to estimate the distance to the presented stimulus. Using this method, each participant was asked to report the magnitude of a stimulus that corresponded to some proportion of the standard. The participant then assigned numbers reflecting the adjudged magnitude of his/her subjective experiences to each stimulus. In the magnitude estimation practice, each stimulus was assigned a number that reflected its distance as a proportion of the standard. The standard stimulus was set as “100.” Thus, if a test stimulus was subjectively twice as far as the standard, a participant was expected to assign it a magnitude of “200.” Under the three device conditions, each participant performed five trials for each of the four test stimuli in Short Range, and five trials for each of the five test stimuli in Long Range.

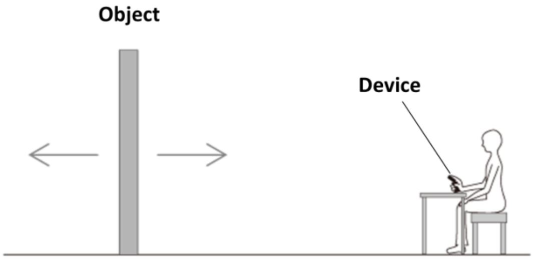

Figure 5. Setup used in Experiment 1: participants sat in front of a table on which one of three devices remained fixed. Experimenters randomly moved the object to change the distances between the object and the device.

C. Result and discussion

The product-moment correlation coefficient (*r*) between the presented distance (the presented stimulus) and the estimated distance (the distance participants estimated) by each device was computed. It was computed for each group, each device, and for both the Short and Long Range scenarios. We categorized both congenitally impaired and adventitiously impaired adults as "visually impaired group," because there was no significant difference between them, and compared the group with "sighted group." In the Short Range scenario, the product-moment correlation coefficients when the visually impaired group used FB-Finger, Vibratory device, and Sonar device were 0.918, 0.742, and 0.763, respectively. When the sighted group used those devices, the correlation coefficients were 0.882, 0.730, and 0.740, respectively. In the Long Range scenario, the correlation coefficients when the visually impaired group used FB-Finger, Vibratory device, and Sonar device were 0.908, 0.663, and 0.461, respectively. When the sighted group used those devices, the correlation coefficients were 0.928, 0.777, and 0.422, respectively. Without regard to each device, each group, or each range, the estimated distances were correlated with the presented distances. Remarkably, FB-Finger exhibited the highest correlation between the presented and estimated distances.

Figures 6 and 7 show the regression lines for the overall data of each device, calculated using the least squares method. These figures indicate that the farther away a stimulus was presented, the farther the distance was estimated. From the abovementioned correlation coefficients and the regression lines, it was found that FB-Finger provided participants with the most accurate estimation of the distance to the presented stimuli.

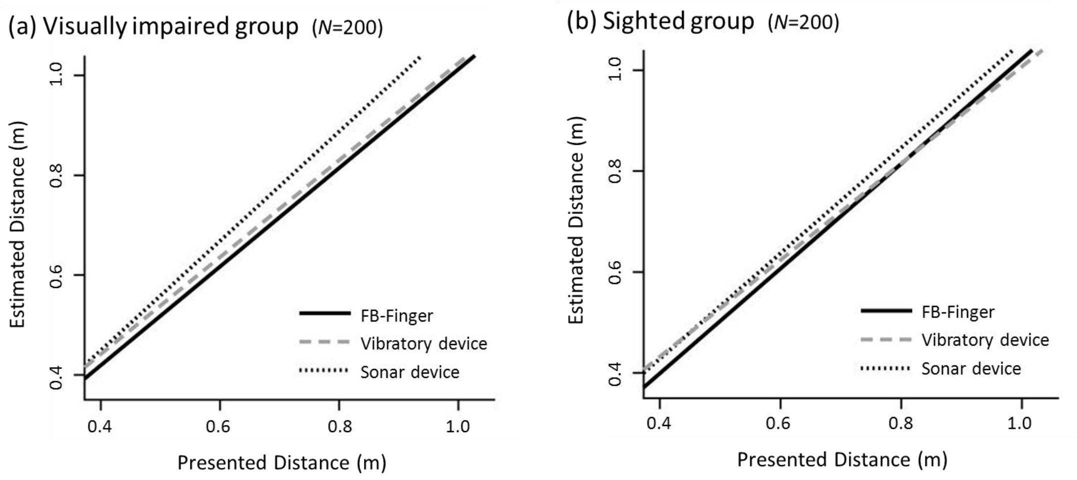

Figure 6. Regression lines for the overall data in the Short Range setup, calculated using the least squares method.

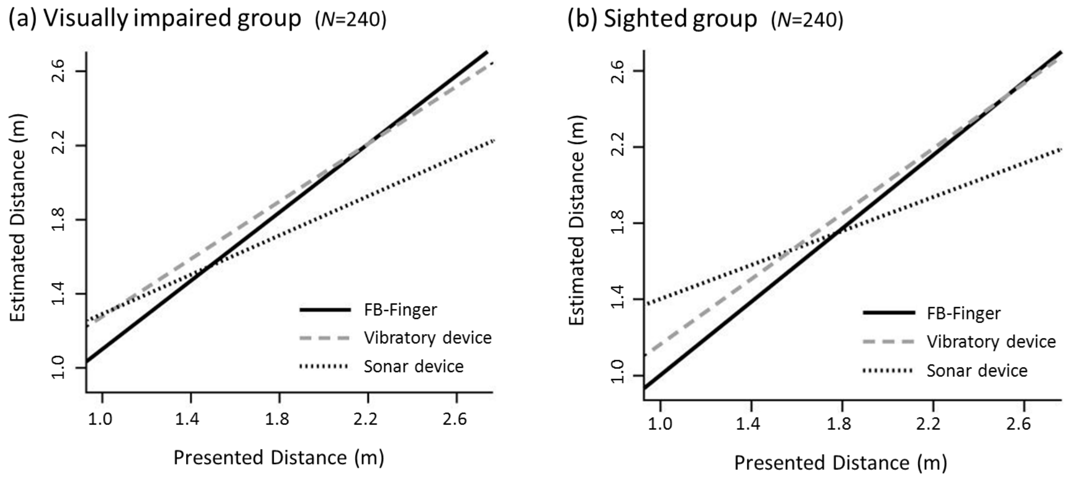

Figure 7. Regression lines for the overall data in the Long Range setup, calculated using the least squares method.

Determination coefficients (square of *r*) were also computed for each participant. Figures 8 and 9 show the mean determination coefficients of each group in the three device conditions. In the Short Range scenario, the mean determination coefficients of FB-Finger, Vibratory device, and Sonar device were 0.872, 0.622, and 0.660, respectively, for the visually impaired group. They were 0.813, 0.647, and 0.744 for the sighted group, respectively. In the Long Range scenario, the mean determination coefficients of each device were 0.878, 0.608, and 0.294 for the visually impaired group, and 0.884, 0.746, and 0.255 for the sighted group, respectively.

A two-way analysis of variance was performed on both the Short and Long Range scenarios by setting both visually impaired and sighted groups as a between-subject factor, and three device conditions (FB-Finger, Vibratory device, Sonar device) as a within-subject factor. The results indicated the same significant main effects of device condition (ps < 0.01) for both the Short and Long Range scenarios. Similarly, multiple comparison tests between the three devices found that the distance estimated using FB-Finger was positive proportional to the presented distance with the highest linearity compared to the other two devices. By contrast, there was no significant difference between the visually impaired and sighted groups. These results demonstrate that FB-Finger endows users with two advantages that cause it to excel above other devices: (1) better estimation of distance, and (2) capability of assisting users with accurate detection of distance.

Evaluation of the output interfaces of Sonar device (pitch of sound), Vibratory device (mechanical vibration), and FB-Finger (lever motion) showed that they all required users to use their bodies/senses to hear sound, feel vibration with skin, and feel finger movement. The findings from Experiment 1 suggest that finger movements, or finger joint motions, most effectively transfer distance information to users.

V. PSYCHOLOGICAL EXPERIMENT 2: FINGER FIXATION ON ACCURACY OF DISTANCE ESTIMATION

A. *Purpose*

In Experiment 1, the participants placed a finger on the lever of FB-Finger but the finger was not fixed to the lever. This may lead them to have a wrong perception of the angular motions of the lever. Hypothesizing that the participants may be able to estimate distances entirely based on the information conveyed from FB-Finger, we conducted another experiment (Experiment 2) to demonstrate the effect of fixing finger joints on the lever of FB-Finger to estimate the distance.

B. *Method*

1) Participants: 16 sighted adults participated in the experiment. Their ages ranged from 21 to 23 years. Of the 16, eight participants were asked to wear blindfolds and were randomly assigned to each experimental condition (given below).

2) Object for Stimuli: We used the same object for stimuli as Experiment 1.

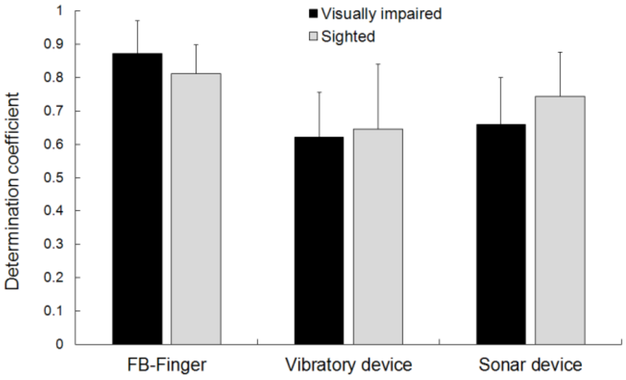

Figure 8. Mean determination coefficients in Short Range setup in the three device conditions for each of the visually impaired and the sighted groups. Standard deviations are shown as error bars.

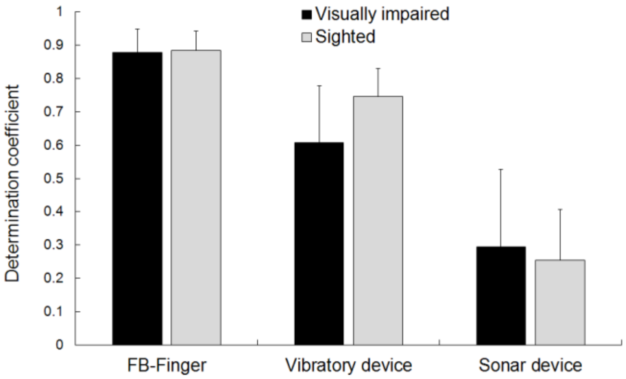

Figure 9. Mean determination coefficients in Long Range setup in the three device conditions for each of the visually impaired and the sighted groups. Standard deviations are shown as error bars.

3) Experimental condition: We adopted two experimental conditions: Fixing condition and Non-fixing condition. In the Fixing condition, shown in Figure 10, each participant's forefinger was affixed to the lever of FB-Finger using a Velcro touch fastener. In the Non-fixing condition set, the forefinger was not affixed to the lever (the same condition as in Experiment 1).

4) Procedure: FB-Finger was used to estimate distances. The standard stimulus was set at a distance of 0.4 m, and one test stimulus was respectively positioned at 0.4, 0.6, 0.8, 1.0 and 1.2 m. Each participant performed six trials for each of the five stimuli. Other procedures (experimental setup and magnitude estimation method) were the same as in Experiment 1.

C. *Result and discussion*

Product-moment correlation coefficients (*r*) were computed for each condition. The *r* values of the Fixing condition and the Non-fixing condition were 0.965 and 0.938, respectively. This suggests that the distances estimated were more correlated with the presented distances in the Fixing condition than in the Non-fixing condition. Statistical analysis found that there was a significant difference between the Fixing condition and the Non-fixing condition ($z = 2.515$, $p < 0.01$). From this result, it is clear that an FB-Finger user is able to estimate the distance between himself/herself and an object more accurately when his/her finger is properly affixed to the lever.

In the Fixing condition, the forefinger was affixed sufficiently tightly that the finger was likely to follow a link-angular motion completely and its joint(s) and skin become more sensitive to somatosensory stimulation with their haptic sense. A finger’s haptic sense to somatic stimulation is considered to be effective to obtain distance information. It is remarkable that FB-Finger enabled blindfolded, sighted participants to correctly determine the distance to an object, even though the individuals had little experience with haptic exploration of the surroundings using FB-Finger. Taking into account the fact that the visually impaired have higher somatic sensitivity than the sighted, it is conceivable that the results from Experiment 2 will lead to the development of some promising applications of FB-Finger for the visually impaired.

VI. “TWO DEGREES-OF-FREEDOM” PROTOTYPE OF FB-FINGER2

Toward upgrading of the functionality of FB-Finger to perceive shapes, we developed an FB-Finger designed with 2-DOF (Figure 11, hereafter “FB-Finger2”). A user holds this device with forefinger on the lever, as can be seen in Figure 12(b). The lever consists of two components with two servo motors attached for each. One servo motor controls the distal interpharangeal (DIP) joint of the forefinger, and the other the proximal interpharangeal (PIP) joint of the finger. The distances from FB-Finger2 to three points (p_1, p_2, and p_3) on the surface of the object, as can be seen in Figure 12(a), were measured using a depth camera (ASUS Xtion Pro Live, hereafter referred to as “Xtion”). This was connected to a Microsoft Kinect to show the depth image of the measured object. On the basis of the measured distances between Xtion and p_1, p_2, and p_3 (referred to as d_1, d_2, and d_3), the angles of the finger’s DIP joint (θ_1) and PIP joint (θ_2) were calculated using the following equations:

$$\theta_1 = \arctan\frac{d_1 - d_2}{v_1}$$

$$\theta_2 = \arctan\frac{d_3 - d_2}{v_2}$$

Here,
v_1: vertical distance between p_1 and p_2,
v_2: vertical distance between p_2 and p_3.

The distance was set as 20 mm with adequate selection of the acquired depth image by Xtion. To cover the user’s

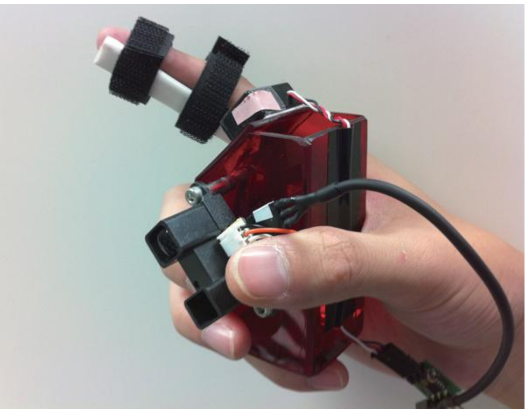

Figure 10. A finger affixed to the lever of FB-Finger.

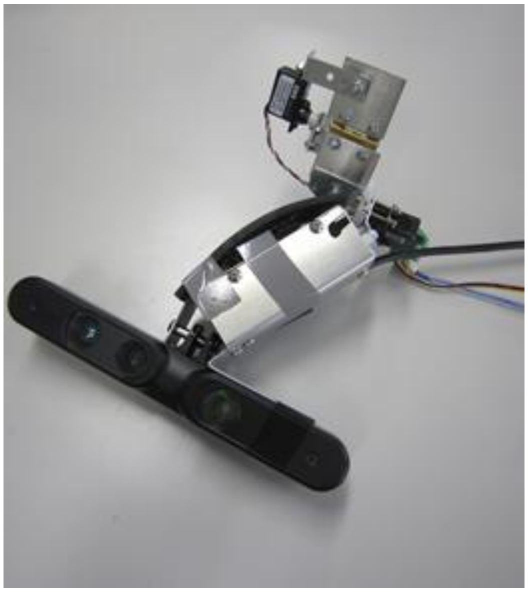

Figure 11. Prototype of FB-Finger2, designed with 2-degrees-of freedom.

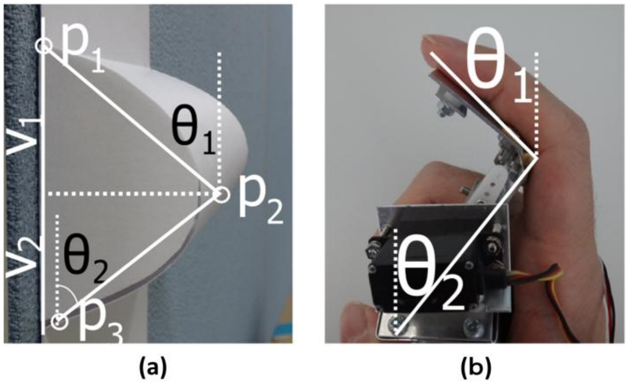

Figure 12. Measuring the distance to an object using the depth camera of FB-Finger2: (a) three points on the surface of the object were measured, (b) a user holds FB-Finger2 with forefinger on the lever.

finger motion, θ_1 ranged between -10 deg and 90 deg, and θ_2 ranged between -40 deg and 90 deg.

Figure 13 shows the system configuration of the FB-Finger2 prototype developed. The distance to the targeted object is measured using a PC-controlled Xtion. The PC also controls two servo motors that are attached to levers 1 and 2. The levers correspond with the movements of the DIP and PIP joints of the user's forefinger. The servo motors are controlled by microcontroller (Cypress's CY8C24123) from the PC control command. To accommodate various finger sizes, the lengths of levers 1 and 2 are set at 25 mm and 30 mm, respectively. The weight of the developed FB-Finger2 is 100 g (without Xtion). The distance range measurable by Xtion is between 0.8 m and 3.5 m, and its depth resolution is 10 mm.

To verify the performability of FB-Finger2, we conducted a preliminary experiment with 12 sighted adult participants. The participants were asked to wear blindfolds and use either FB-Finger or FB-Finger2 to identify the shape of objects (triangle, rectangular, trapezoid, semicircle). All participants identified triangular and rectangular objects more accurately when they used FB-Finger2 than when they used FB-Finger, but no such difference was found when they tried to identify trapezoidal and semicircular objects. The results of this experiment partially verify the performability of the 2-DOF in FB-Finger2. However, further studies on the method for measuring the depths of an object and for outputting information are necessary.

VII. CONCLUSION

The development of FB-Finger was inspired by the "smart" mechanism and the ecological interface design. As a novel SSD, FB-Finger is primarily aimed at helping the visually impaired to "feel" and "recognize" their surrounding environment. The current device comprises a sensor unit (one of two different types of sensor units) and a small actuator. One type of sensor unit radiates ultrasonic waves or infrared rays to measure the distance between the user and an object. The other type of light sensor unit measures luminous intensity. An actuator transmits the distance or luminance level into the haptic sense of a finger as somatosensory stimulation via a link-angular motion. This represents a form of ecological interface, in that information on distance and brightness is directly converted to another sensory modality. This paper focused on forefinger skin and joints to determine how somatosensory stimulation helps to improve the performance of FB-Finger.

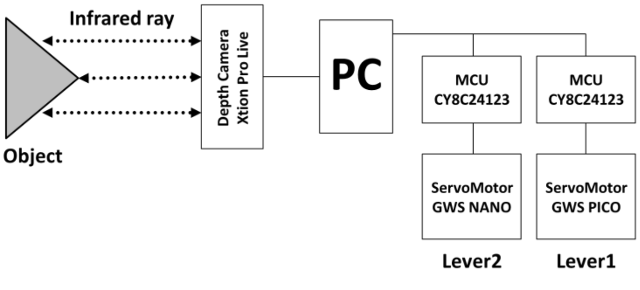

Figure 13. Block diagram of FB-Finger2, which we developed, with depth camera.

Two experiments were conducted to verify the feasibility of FB-Finger. The results of Experiment 1 demonstrate that FB-Finger is more accurate than commercial products, and has the highest linearity in estimating distances. The results of Experiment 2 clarified that users are able to estimate distance more accurately when the joints of their forefinger are fixed at a 1-DOF link with FB-Finger.

The findings obtained from these two experiments suggest the following: First, finger joints motion ("somatosensory feedback") provides users with richer spatial information than tactile or auditory feedback. Second, FB-Finger can serve as a useful travel aid. It can help the visually impaired avoid obstacles and find landmarks such as poles, bus stops, and trash cans, while walking, particularly when used along with a cane or a guide dog. In order to verify its usefulness, we will ask visually impaired participants to use FB-Finger along with a cane and walk on roads, avoiding obstacles or detecting landmarks in a more real environment like city streets, where the obstacles and/or the users are moving. Third, FB-Finger can help to enhance quality of life for visually impaired persons.

We conducted two further case studies in accordance with the progress of our research. From the first case, we found that FB-Finger, when equipped with an infrared ray sensor, enables users to "feel" the outline of objects in display windows. In a test at a museum, FB-Finger users managed to feel the contour of exhibits contained in glass cases without touching and seeing them, as illustrated in Figure 14.

In the second case study, in order to obtain suggestions regarding the potential for a variety of applications, we conducted a small workshop in which visually impaired participants were asked to use FB-Finger with a light sensor

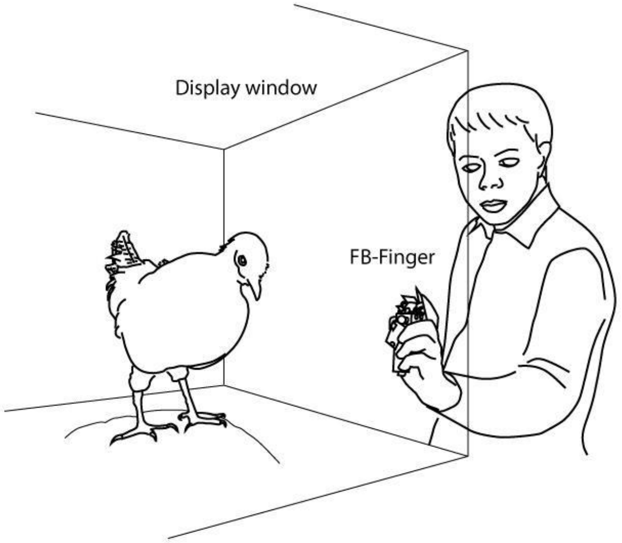

Figure 14. "Feeling" an exhibit in a display window using FB-Finger: A scene from a demonstration in a museum.

unit (see Section III) to "feel" several events, such as a flame of fire, pendulum motion, and a rolling ball, without touching. The results were better than what we expected; visually impaired children as well as visually impaired adults were able to "feel" and recognize a flame, as illustrated in Figure 15, the direction of pendular motion, and an approaching ball. Thereby, we confirmed that FB-Finger can be applied to devices that allow visually impaired users to obtain knowledge of events that are impossible to touch, even though we do not yet have quantitative evidence. In other words, these findings indicate that FB-Finger can facilitate recognition of the surroundings without visual modality.

FB-Finger currently still needs improvements. First, its distance measurement capabilities need to be consistent when nearby objects emit infrared rays.

Second, though the sensors have a theoretically high resolution in daily use, the actual resolution of our device is lowered for a few reasons. These reasons include a servo motor's control noise (small vibrations even in stable condition), analog-to-digital converter's noise, and quantization error. In real situations, we expect that a user will move around his/her hand holding the FB-Finger to perceive the distance of surrounding objects and their direction, so that such activities enhance the perceptual resolution of our device such as "active touch" [27]. We will continue to improve FB-Finger to eliminate factors that disrupt the device's resolution. We will finally improve FB-Finger so that it can convey information for various textures of objects.

Third, the sensor needs to be replaceable between infrared rays and ultrasonic waves, so that users can use an appropriate sensor depending on the scenario. In order to allow the use of more than two sensors, there are some alternative methods. One is to let the user manually select an individual sensor, and the other is to select or integrate a sensor automatically, which is called "sensor fusion." We hypothesize that the manual switching has an advantage in normal use, because humans are smarter and more flexible as compared to artificial intelligence, and can adjust to complex and various environments. Consequently, users will be able to handle FB-Finger effectively. In one of our future works, we will develop two versions of FB-finger: one with manual sensor switching, and the other with "sensor fusion," in order to compare their usability.

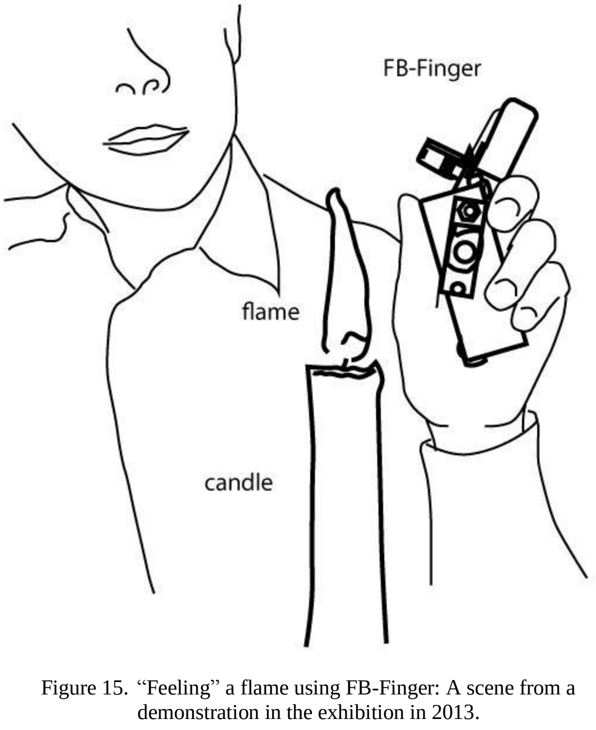

Figure 15. "Feeling" a flame using FB-Finger: A scene from a demonstration in the exhibition in 2013.

Fourth, the distance sensors need to be applicable to both Short and Long Range scenarios to allow for measurement of more expansive locations.

Fifth, we will take the output interface into account. It should be possible to have another method of conveying distance information via somatosensation, besides finger joints motion. A laparoscopic surgery simulator with the haptic device, employing force sense feedback, has been commercially available recently [28]. This product ensures that force sense can be used for the feedback interface. In the further improvement of our device, we will consider multiple somatosensory feedback interfaces by adding force sense to lever angular motion.

FB-Finger2 was developed to capitalize on the movements of finger joints for more accurate distance estimation, but it also needs to be improved. The prototype system is too large to be portable. Consequently, it is necessary to downsize it to a size similar to that of FB-Finger. Moreover, in order to obtain information on surrounding objects or their textures, Microsoft Kinect should be used effectively. Zöllner et al. recently developed Mobile Navigational Aid for visually impaired persons based on Microsoft Kinect [29]. This Aid system uses two cameras of a Kinect separately. An RGB camera is used in "micro navigation," and a depth camera is used in "macro navigation." In a similar manner, we will improve FB-Finger2 so that it can be equipped with sensors and information processing system available in Kinect.

To ensure availability, applicability, and ease of use, SSDs and ETAs should be capable of being held in one hand. They should be capable of assisting users with exploration of their surroundings, i.e., detection of distance and direction to nearby objects, accurate perception of the shape of objects, and recognition of events or objects that cannot be physically touched. Such spatial information will help users to avoid collisions with obstacles and to approach objects. FB-Finger encourages visually impaired persons to acquire knowledge about events that they have not experienced before. Additionally, FB-Finger devices should be manageable by anyone, regardless of age or cognitive ability, and they should require little knowledge or skills in understanding the signals emitted by the devices. If a user can easily replace the sensor with a different one, FB-Finger can respond to demands under various situations. On realizing this improvement, we guarantee that users will receive full benefit from our developed device.

In this study, we verified that FB-Finger can fulfill the requirements of visually impaired people. To enhance the usability of FB-Finger or FB-Finger2, we will continue experimental studies, analyze the results, make necessary improvements, and enhance the performance in traveling and exploring environments. The device presented in this paper is functionally promising and we expect to make the device function as a part of the body for both visually impaired and sighted people to develop their potential capabilities. If this idea of "Extended Body" is realized, our device can assist users in improving the quality of life.

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