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Navigation Using a Haptic Hand-Mounted Device For the Visually Impaired

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***Abstract*— For those with no or limited sense of sight, navigating through the world can be a challenge. The visually impaired must rely on senses other than sight such as hearing and touch to guide them. The walking cane has been the traditional navigational tool for the bind, but it offers only a limited sense of the environment that is focused mainly on protecting the legs and feet, and does not indicate when the person is approaching a hanging object. The motivation is to replace the walking stick with something that can detect objects in the immediate vicinity of the person. A sonar sensing modality will be used to gather information about the environment, and then feedback will be delivered to the user by varying vibration stimuli. The vibrotactors are mounted on a glove to allow the user to point the device in any direction. This has the advantage of having as many degrees of freedom as the hand and requires fewer actuators and sensors compared to a head-mounted display. The efficacy of the device and how humans respond to vibrotactile feedback to navigate through a complex environment will be evaluated by having a series of blindfolded subjects try to navigate a course filled with various obstacles. Trials were completed with both the glove and the walking stick and a dynamic environment was introduced in half of the trials. Results show that the glove does not perform up to the standard of the walking stick but may be improved with future work.**

***Index Terms*— Haptics, vibrations, blind, ultrasonic.**

I. INTRODUCTION

Visual impairment and blindness afflict a significant portion of the world population. The World Health Organization (WHO) reported in 2002 that 161 million people are visually impaired, of that 37 million are blind [1]. The distribution of blind people is non-uniform, with the majority coming from developing nations. There is thus a need for inexpensive devices to assist blind and visually impaired people.

The visually impaired rely on their other senses to help navigate though the world. Hearing allows them to gage distances and hear an oncoming object. The sense of touch is just as important for the blind, allowing them to feel objects around them. Like sighted people, the blind use tools to help them in their daily lives. The traditional navigational tool for the blind is the white cane or walking stick. The use of walking sticks by the blind dates back to antiquity while the modern white cane was developed after World War II [2]. The white cane is the most inexpensive and most visible of the current options available to the blind. Canes, however, are only able to sense one direction at a time. For example, a person walking with a cane touching the ground will be unable to sense hanging objects. Guide dogs are also available for the visually impaired, usually for free, but can cost up to $42,000 to train [3]. While guide dogs provide the blind with a larger sense of their surroundings, their limited availability and a usefulness of 6 to 8 years mean that they are not always an option. White canes and guide dogs are also very visual reminders to others of their visual impairment. Any navigational device would be likely to augment or supplement these methods because of this association.

The goal of this paper will be to develop a haptic device that can sense the surroundings through a sensor and relay that information to the device user through vibrotactors. Previous devices have been developed and tested with similar goals. These devices varied in where they were located, how the information was gathered, and how the vibrations were administered. Devices have been mounted on shoes, helmets, wrists, and traditional canes [4], [5], [6], [7]. The device we propose and test in this paper is based off of the Tacit device [6]. This device is wrist mounted with two sonar sensors for object detection and two servomotors for feedback. There is a sensor-servo pair for right and left and the vibrations scale in intensity with closer distances.

Our goal is to make a device similar to this with sonar sensors and vibrotactors for feedback. We will then validate the device by a series of tests in an obstacle course designed to simulate a modern environment, including both static and dynamic objects. The time that it takes the participants and the frequency of hitting objects will be compared with traditional walking stick usage to validate the device.

II. BACKGROUND

A. *Previous Devices*

There have been many proposed devices for haptically assisted devices for the visually impaired. The major differences between the devices are where they are mounted or worn, how feedback is delivered, and how the surroundings are detected. We begin our discussion with an overview of these devices.

Sharma created a haptic device that can be installed in a shoe [4]. This device receives GPS information from a smartphone and provides vibration feedback at the right, left, front, and back of the shoe in order to provide guidance to a destination. Additionally, a proximity sensor in the front of the shoe can detect objects up to 3 meters and provide vibrational feedback. This device is unobtrusive but it can only sense low to the ground objects. Also, since

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only 4 vibrotactors are used to indicate direction, conveying intermediate directions is impossible.

Santiago Praderas et al developed a head mounted device called the Cognitive Aid System For Blind People (CASBliP)[5]. This device uses two mounted cameras to provide stereo imaging that is translated into audio which is played through headphones. This method allows differentiation between static objects from 0.5 to 15 m. Akhter et al proposed a similar stereo imaging system using a smartphone camera and catadioptric imaging rig [8]. The two image system allows for accurate distance detection by comparing the right and left images. This is an accurate system but requires precise calibration and the camera system is larger, more fragile, and more expensive than other sensors. Audio output is less ideal than haptic feedback. The visually impaired rely on their hearing to navigate and it is preferable to reduce any additional noise in their environment.

The Haptic Alerts for Low-hanging Objects (HALO) is a device that is mounted to a traditional walking stick and is designed to sense objects at head level that a white cane on the ground would miss [7]. This uses an ultrasonic range sensor to detect overhead objects and an eccentric motor to vibrate when an object is detected. This has an advantage of attaching to the most widely used blind navigational tool and being inexpensive. Wang et al demonstrated that this device was successful in allowing users to avoid low hanging obstacles. This device is passive the majority of the time, only activating when an object interrupts the range sensor. Active exploration of the environment is impractical in this design configuration since the sensor is attached to the middle of the walking stick.

The Tacit project was developed as a wrist mounted detecting device [6]. It uses two ultrasonic range senors for detection and two servomotors for haptic feedback. There is a sensor-servo pair for each side of the hand to help indicate direction. The servos motions increase in frequency with closer distances, i.e. a nearby object would elicit a bigger response from the servos. Servos were chosen because they are quiet and can be fine tuned to different positions. Being fixed to the hand allows for as many degrees of freedom that the hand has, thus easily allowing the user to point it in the interested direction. Additionally, it doesnt prevent the user from using a white cane or a guide dog and can be worn on either hand.

B. *Device Parameters*

A variety of sensing modalities, mounting configurations, and tactile feedback modes were considered when conceptualizing the design. Before the specific sensors could be determined, the design requirements needed to be considered. The sensors should be able to detect objects at least as far away as the length of the traditional walking cane. Typically, they range in length anywhere from 25 - 63 inches (63 - 160 cm) [9]. Objects beyond this range should be ignored since it may be confusing to the user if they are inundated with irrelevant information. A variety of sensing modalities were initially considered. Infrared range finders were considered, but were quickly eliminated because they are prone to extraneous readings in well lit areas and did not provide a sufficient range for our application. A laser range finder would be ideal due to its precision, but the cost of the sensor made it an nonviable option. Since the majority of the visually impaired come from developing nations, the price would prevent them from using the device. The final sensing modality that was considered is sonar. We determined this was the best option because it has a range of 6 inches to 6 feet (15 cm to 2 m), which is within the design requirements and it is only marginally more expensive than the infrared sensors. Image based sensors were not considered due to their size and expense.

The type of haptic feedback to deliver was determined based on the information we are trying to convey, what information receptors are capable of receiving, and what space we have available to package the device. For example, the Tacit project uses servo motors to vary pressure linearly with distance. This conveys the same information we are trying to convey - the distance and direction of the object by exciting the merkel receptors. However, the servo motors are bulky and add significant mass to the device. The HALO device only conveyed whether or not an object was present, so they used a eccentric mass motor to give short pulses to the user, exciting the pacinian receptors. This met the space and mass requirements, but it does not effectively convey distance or direction. We opted to use an eccentric mass motor to convey the presence of an object, and used asymmetrical beat frequencies to vary the vibration characteristics of the motor. More intense vibrations correlate to a closer object, and less intense vibrations correlate to a further object. The scale of the frequency range was determined by the best frequencies to excite this receptor type (10-500 Hz).

As can be seen in the background section of this paper, there are a plethora of possible mounting configurations for the device. It may be head mounted, worn as a glove, embedded in a shoe, or any other place where pacinian receptors have high density or a large workspace. The head mounted configuration could be stigmatizing when the user walks around with it in public, so this option was immediately discarded. The next criteria that eliminated most of the other options is the number of vibrotactors needed to convey the information. For example, at least four of the shoe-mounted vibrotactors are needed to convey direction. The hand-mounted configuration requires the least number of vibrotactors because the natural kinesthetic feedback the user receives from pointing the device provides direction information, and thus only distance needs to be conveyed.

III. PROJECT DESCRIPTION

The design consists of a parallax PING))) ultrasonic sensor, 4 vibrating disk motors, an Ardurino Uno microcontroller, and a housing prototyped using a 3-D printer. The assembly is velcroed to the upper portion of a glove the user is wearing.

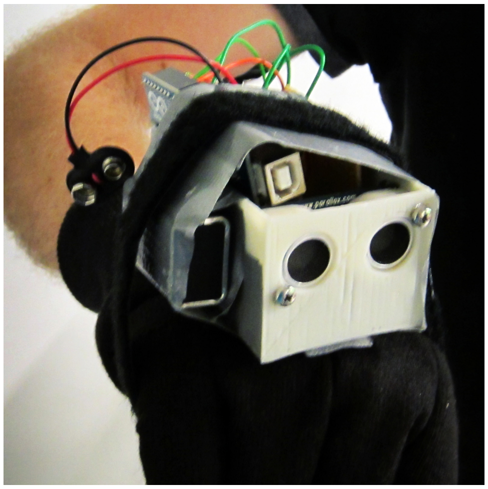

Fig. 1. Prototype Device

A. Ultrasonic PING))) Sensor

The PING))) sensor works by sending out a short burst of ultrasonic sound (40 kHz) and receiving the return echo. The sensor sends the output pulse until the return pulse is detected. The length of the pulse corresponds to the object distance. Objects that are small, reflective, observed from a shallow angle, or beyond the detection range are not detected. In addition, soft objects that absorb the sound waves are not detected properly. The device is not designed for outdoor use, so future designs should protect it from moisture. The calculated distance also assumes that the temperature is constant. If the device is used in a range of environments, errors of up to 12

- Supply voltage: +5 VDC
- Supply current: 30 mA typ; 35 mA max
- Communication: Positive TTL pulse
- Package: 3-pin SIP, 0.1 spacing (ground, power, signal)
- Operating temperature: 0 70 C.
- Size: 22 mm H x 46 mm W x 16 mm D (0.84 in x 1.8 in x 0.6 in)
- Weight: 9 g (0.32 oz)

B. Arduino Uno Microcontroller

The Arduino Uno microcontroller is interfaced with a computer via USB, but may also operate from an external power source and run independent of the computer, storing the program in the EEPROM. It is programmed using the Arduino software, which is based on C++. A 9 V battery is used to supply power to the board. A voltage regulator reduces this to 5 VDC. Each pin can draw or source up to 40 mA. 4 of the 6 pulse width modulation (PWM) pins are used to operate the vibrating motors. One digital pin is used for the PING))) sensor. [11]

- Opperating Voltage: +5 VDC
- Input Voltage: 7-12 V
- Digital I/O pins: 14 (6 for PWM)
- Analog Input Pins: 6
- DC Current per I/O Pin: 40 mA
- Flash Memory: 32 kB
- EEPROM: 1 kB
- Clock Speed: 16 MHz

C. Housing

The housing is designed to protect and neatly package the components discussed above. The size of the housing was determined by the size of the electronics and was influenced by the size and shape of the human hand. Average hand dimensions were used and a curved bottom was added for additional comfort. [12] The PING))) sensor is at the front of the housing, where there are cutouts for the sending and receiving parts of the sensor. A spacer is placed over the protruding cylinders of the sensor so they can be bolted into the housing without revealing the sensor to the elements. The microcontroller sits behind the sensor. In the origional design, the Ardurino Mini was used, which is considerably smaller than the Ardurino Uno. For this reason, the Uno does not fit completely inside the housing. It was placed inside the housing as much as possible, and held in place by duct tape. The back plate of the housing has a hole cut out for the potentiometer on/off knob. the 9 V battery is attached to the back of the device via duct tape since the microcontroller was over-sized and didnt leave enough room. The vibration motor wires are fed through the bottom of the housing and the motors are attached to the bottom plate. A strip of velcro is attached to the bottom of the plate on top of the motors so the device will stick to the glove. This slightly dampens the motor vibration, but it can still be felt through the glove.

D. Microcontroller Circuit and Program

A potentiometer is used to turn the vibrating motors and ultrasonic sensor off to conserve power when the device is not in use. The main loop only runs when the resistance of the potentiometer is above the threshold, corresponding to a value of 500 in the Ardurino program. When the device is powered, 5 V DC, ground, and a control signal are sent to the ultrasonic sensor. An output signal is sent, and the time it takes for the signal to return is measured. The time is then converted to a distance using the speed of sound in air at room temperature (1130 ft/s). A cutoff distance of 48 inches was defined so no vibration will occur if something is detected beyond this distance. This was done to match the walking stick we used in the trial and to eliminate the effect of faraway objects that may cause confusion to the user. Each of the vibrating motors is connected to a PWM pin so the voltage and subsequent vibration intensity may be varied based on the returned distance. Inside the distance threshold, the PWM value sent to the motors is scaled. The maximum vibration intensity is multiplied by a value between 0 and 1 which is determined by the equation:

$$scale = 1 - \frac{inches}{MasDistance} \tag{1}$$

Where inches is the calculated distance to the object and MaxDistance is defined as 48 inches. This produces the effect of intense vibrations for objects near the device, and minimal

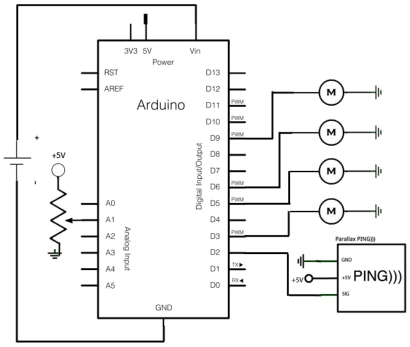

Fig. 2. Device Circuit

Fig. 3. Experimental Course

vibrations for objects that are far away. See Figure 1 for wiring.

IV. EXPERIMENT

The experiment devised to validate the device consisted of 8 different trials. Through all of these trials, the subjects were blindfolded to simulate blindness and wore headphones playing white noise. The white noise was used to block the sounds made by the vibrating motors to ensure that subjects were alerted haptically and not through any other senses. Two obstacle course were designed for subjects to navigate through with the devices. Objects of varying size, ranging from about 1 foot tall to about 5 ft tall were placed in semi-random positions. Each course also contained one hanging object. The courses were roughly 20 ft long and 10 ft wide. In half of the trials, subjects were given the glove to navigate though the course and in the other half, they were given the 4 foot long walking stick. Additionally, half of the trials will have a dynamic environment. The course will remain the same but there will be a person walking through a set route at a constant speed. This resulted in eight total trials. Before each subject began, the order of the trials were randomized. This was done to help reduce any learning effect of the different courses. The subject was then blindfolded, given the headphones to wear, and instructed to navigate to the other side of the course when they were tapped on the shoulder. Each trial was timed and the number of times they bumped into an object was tallied. Multiple bumps that occurred very quickly after the other were counted as one. They were informed when they reached the end of the course and were led to the beginning to begin the next trial. Each course was randomized slightly using the same objects every few trials to ensure that subjects did not learn the courses. Figure 2 shows one of the courses created for the experiment.

V. RESULTS AND DISCUSSION

ANOVA tests were performed on the gathered data. The variables considered for the ANOVA tests were subject, course, device, trial type, time, and bumps. Subject represented the seven subjects, course was either course 1 or course 2, device was either the glove or the stick, trial type was either static or dynamic, and time and bumps were the gathered data. The first ANOVA test considered the subjects, course, and device in regards to number of bumps. The only statistically significant result from this was the device type, $F(1, 55) = 34.98$, $p = 0$. Considering the bumps in regard to trial type resulted in no significance. The second ANOVA test considered the subjects, course, and device in regards to time. This showed that the device type was significant, $F(1, 55) = 16.46$, $p = 0.0002$. Trial type was not significant when compared with time. Figures 3 and 4 show the post hoc results for both bumps per trial and time per trial for the two devices, the glove (device 1) and the walking stick (device 2).

The results indicate that the haptic glove performs significantly differently than the traditional walking stick. On average, the glove trials had 5 more bumps per trial and took 50 seconds longer than the walking stick trials. During the walking stick trials, subjects bumped into less objects because they could feel them with the stick more easily. The most bumps in these trials came from the hanging object. While wearing the glove, subjects had difficulty orienting themselves and creating a frame of reference. Often the first indication of an object was bumping into it. This physical contact seemed to guide the subjects as well as the glove. With the glove, it was hard to tell where to point it to find objects. We hypothesized that giving the device the same degrees of freedom as the hand would allow the subjects to be able to sense in any direction they wanted. The issue with this assumption is that without a reference frame, it is difficult to know where there is an area of interest to point the device. When we use our sense of sight, we can see on the periphery as well as what is in front of us. This allows us to be aware of points of interest to look at. This is difficult to simulate with tactile feedback and the results confirm this. The kinesthetic feedback from the walking stick has an improved periphery perception as seen in the data. The experiment shows that kinesthetic feedback is more important in perceiving surroundings than tactile feedback.

While there was no learning curve indicated from the ANOVA results, the experience from the experiment showed that the glove required a certain amount of practice before understanding it fully. For example, some subjects held their hands in different positions and angles to get the best

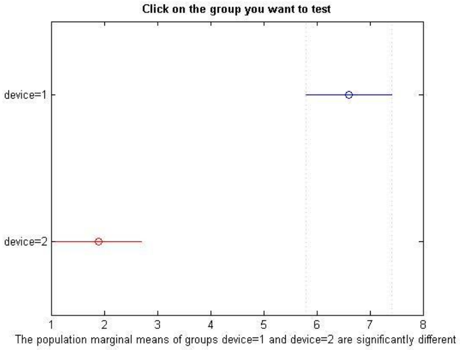

Fig. 4. Bumps Post-Hoc ANOVA

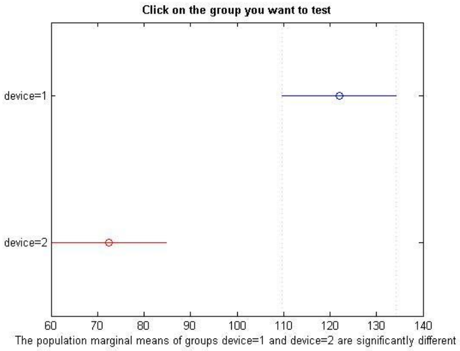

Fig. 5. Time Post-Hoc ANOVA

feedback. One participant held his hand upside down. A flaw of the glove is that it is not immediately intuitive how to position the hand.

VI. CONCLUSION AND FUTURE WORK

The results from the experiment show that the haptic glove developed in this paper did not perform as well as the traditional walking stick. The experiment did, however, show that the device can be used to navigate a complex environment with objects of varying height, hanging objects, and even moving objects. An interesting result from the experiment shows that kinesthetic feedback is more important for physical navigation than tactile. While the device did not perform to the current standard of the visually impaired, there is potential in the concept and could be further explored. Options for future work are considered below.

The current design does not consider the effects of temperature on the ultrasonic sensor accuracy. The speed of sound increases with increasing temperature, leading to up to 12

$$V = \frac{1}{12(1130 + 2\Delta T)} \tag{2}$$

Where V is the speed of sound in ft/s, and T is the change in temperature in Fahrenheit.

Different vibration patterns could be experimented with. For example, a compass module could be used to help determine absolute direction. In this case, the user could set a direction as the default direction and if the user gets turned around, a special vibration pattern would be used. Different vibration patterns could be used to indicate right and left if using two sensors. A vibration pattern could also be used to indicate low battery. Battery life is an issue for a device of this type. If a visually impaired person were to run out of battery power, they could be stranded without a navigation device. Solutions could include a rechargable battery, solar cells, or piezoelectric generators.

The microcontroller and ultrasonic sensor are both sensitive instruments and need adequate protection from the elements. Since this device would presumably be used everyday by the user, eventually the device would get wet in the rain. Future housing designs should be sealed watertight. The materials should be chosen so that they do not interfere with the ultrasonic sensor.

In addition, the housing should have a contoured design to conform to the wrist so that the interface between the device and the wrist does not slip or twist. This may help improve the aiming of the device, and provide confidence in the wearer that they are pointing where they intend to point. Additionally, it could angle the sensor so that the wearer will not strain their wrist. It will also allow for a better connection between the skin and the vibrating motors. The motors could be embedded in the strap that surrounds the palm so that they are in direct contact with one of the most sensitive regions of the body, where vibration discrimination may be improved.

An experiment would have to be conducted to validate the placement of the motors. Further items that could be tested are the types of scaling functions that best correlate to the way we perceive distance. In the current design we vary vibration intensity linearly with distance, but perhaps a second order function or an exponential function would help better convey distance. We could test different ways that distance is conveyed by the device. The user could be approaching a plane wall from the perpendicular direction, a transient object could cross perpendicular to their path from different distances, they could approach a convex corner, and they could approach a concave corner. Corners should be fixed to 90. Angle of approach should be kept constant since the distance measurement is sensitive to it. Subjects could be asked to gauge the distance to the stimulus based on the vibration intensity, and also whether they were able to determine whether it was a corner (concave or convex), a wall, or a transient object. The placement of the motors and the type of scaling function could be factors to vary when testing. The error between the estimations and the actual distance could be recorded. It would be interesting to see whether they could correctly choose the type of corner, and also what they are most likely to think it is when they have a false positive. The combination of motor placement and scaling functions that maximizes the number of correct corner type guesses and minimizes the error in distance estimation is desirable.

APPENDIX

Arduino Code used in the device:

```
// Haptic Glove Interface//
```

```
// This code takes an input from a PING ultrasonic sensor and outputs vibration through 4 vibration motors.
// The intensity of the vibration scales with closer distance.
// SETUP CONSTANTS //
// This constant won’t change. It’s the pin number
// of the sensor’s output:
// MaxMotors is the number of vibration motors in the device.
// pingPin is the pin of the PING sensor.
// motorPins is the pins of the motors.
// potPin is the pin of the potentiometer.
// val is the value of the potentiometer.
const int MaxMotors = 4;
int pingPin = 2;
int potPin = 1;
int MotorPins[MaxMotors] = {3,5,6,9};
int val = 0;
double MinVibe = 75;
double MaxVibe = 255;
void setup() {
// Initialize serial communication:
Serial.begin(9600);}
void loop(){
// Etablish variables for duration of the ping and the distance in inches.
double duration;
double inches;
val = analogRead(potPin);
if(val >500) {
// The PING))) is triggered by a HIGH pulse of 2 or more microseconds.
// Give a short LOW pulse beforehand to ensure a clean HIGH pulse:
pinMode(pingPin, OUTPUT);
digitalWrite(pingPin, LOW);
delayMicroseconds(2);
digitalWrite(pingPin, HIGH);
delayMicroseconds(5);
digitalWrite(pingPin, LOW);
// Read in duration of pulse in microseconds.
pinMode(pingPin, INPUT);
duration = pulseIn(pingPin, HIGH);
// Convert the time into a distance.
inches = microsecondsToInches(duration);
// This is the cutoff distance for the device in inches.
double MaxDistance = 48;
// The vibration intensity scales with distance.
// There are four levels of vibration, starting with MaxDistance and each subsequent level is a quarter less.
double scale = 1 - inches / MaxDistance;
double Vibe = scale*MaxVibe;
if (Vibe <MinVibe) {
Vibe = MinVibe;}
for(int i=0; i ¡ MaxMotors; i++) {
if (inches ¡ MaxDistance) {
pinMode(MotorPins[i], OUTPUT);
analogWrite(MotorPins[i],Vibe); }
else{
pinMode(MotorPins[i], OUTPUT);
analogWrite(MotorPins[i],0); } }
Serial.print(scale);
//Serial.print(”in, ”);
delay(100);
Serial.println();
}
else {
// Turn off
pinMode(pingPin, LOW);
for(int n=0; n <MaxMotors; n++)
pinMode(MotorPins[n],LOW);}
long microsecondsToInches(long microseconds){
// According to Parallax’s datasheet for the PING))), there are
// 73.746 microseconds per inch (i.e. sound travels at 1130 feet per
// second). This gives the distance travelled by the ping, outbound
// and return, so we divide by 2 to get the distance of the obstacle.
// See: http://www.parallax.com/dl/docs/prod/acc/28015-PING-v1.3.pdf
return microseconds / 74 / 2;}
```

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