Auditory Spatial Awareness Device for the Visually Impaired

ECE 445 Design Document Part 2

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4/17/2020

1 Introduction

1.1 Objective

There are 36 million people who suffer from blindness around the world, and require mobility aids to help them effectively navigate their surroundings and avoid obstacles [1]. The most common tools used by victims of blindness include white canes and guide dogs [2]. However, both of these tools are problematic for the following reasons:

1) White canes are cumbersome to use in environments with many obstacles. The user may knock down precariously placed items indoors, accidentally hit pedestrians on a crowded sidewalk, etc. These canes only provide information about the environment within a tight radius.

2) Guide dogs require intensive training and a substantial amount of maintenance, so they may not be affordable to all victims of blindness.

Consequently, we aim to develop a cost effective electronic tool that can be intuitively used by blind people to navigate their surroundings. We propose a two-part device consisting of a headset and a handheld device. The handheld device will resemble the body of a flashlight and will use an ultrasonic sensor to detect objects up to 3 meters away from the user. A 3D audio signal (a short beep) will be transmitted to the user via the headset to indicate the presence of an obstacle, and will be varied based on two factors: the distance of the object from the sensor and the angle (horizontal and vertical) of the device relative to the user's head. The distance of an object from the sensor will determine the speed of the signal; shorter distances will result in more frequent beeps. The horizontal and vertical angles of the device will be used to determine a filter that will be applied to the audio signal, so that the source appears to match the physical position of the obstacle.

Since blind people rely heavily upon hearing to create a mental image of their environment, we hope that a 3D audio feedback will enable users to navigate their surroundings in a more natural manner [3]. Moreover, the usage of this device will be similar to that of a white cane so it will be relatively easy for users to learn how to use the device. Its operation is analogous to navigating a dark room with a flashlight.

1.2 Background

In general there are more products utilizing advanced technologies to aid the hearing impaired then there are for the visually impaired. Blind people have a harder time navigating their surroundings than the deaf and there are very few products that offer a solution beyond walking sticks and guide dogs. The proposed solution is inspired by the flashlight and the ability it provides for the user to navigate a dark room by only illuminating a section of the room at a time. The images of the previously illuminated sections are burned into the memory of the user. For the blind, their whole world is one dark room, and we believe that the concept of a flashlight can be ported over to the auditory domain.

1.3 High-Level Requirements

- The handheld component of the device should be lightweight and portable.
- The sensor should provide general object awareness information within 10ft of the user.
- The source of the audio feedback should appear to align with the physical location of the object.

2 Design

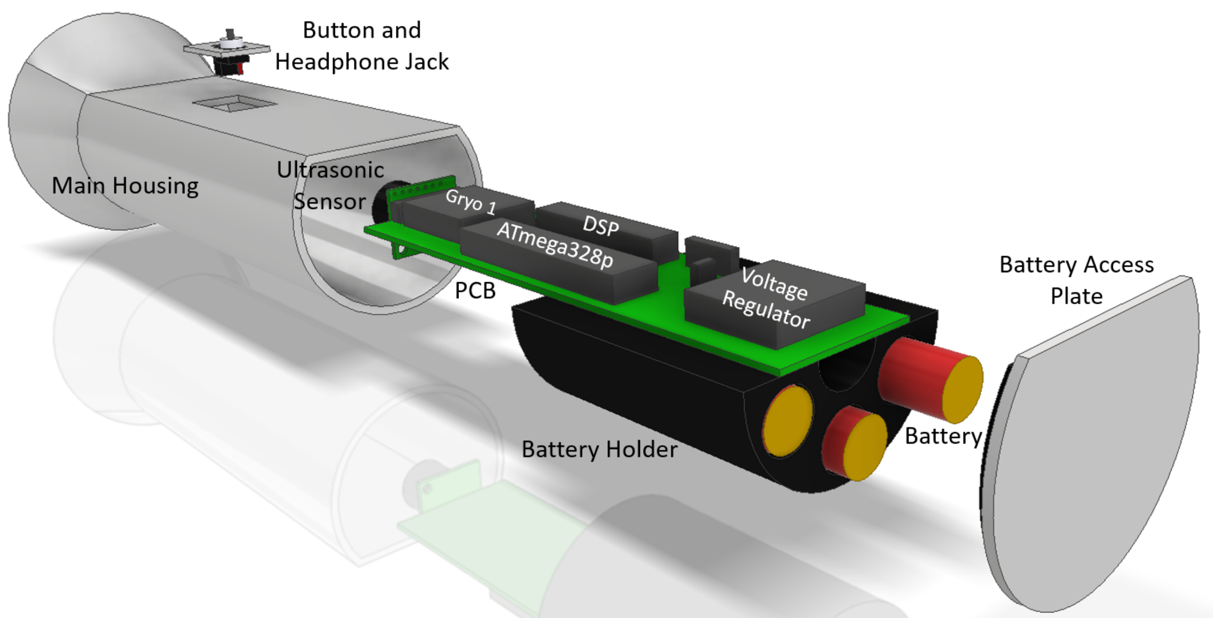

Fig. 1. Physical design and layout of the hand-held component

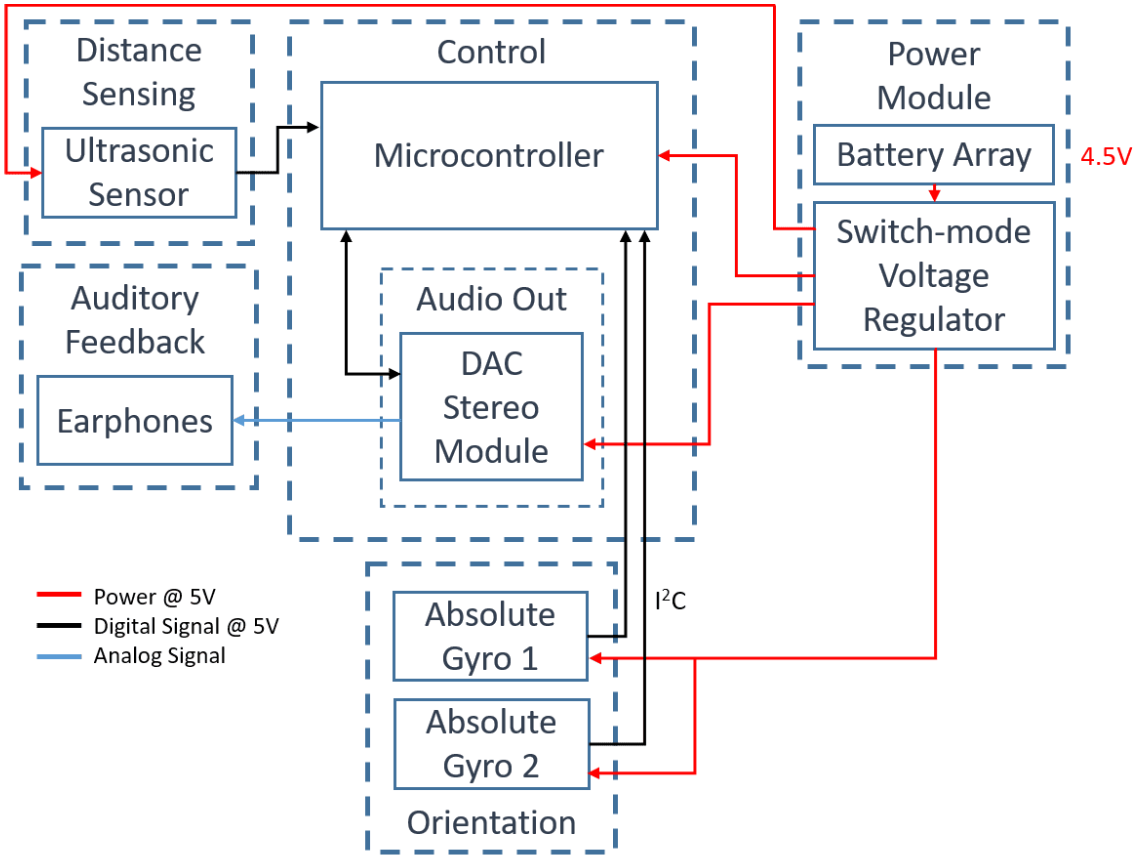

Fig. 2. Block Diagram of Device

2.1 Power Module

2.1.1 Battery Array

For accessibility and simplicity reasons, commercially available battery cells will be used in an array as the main energy source to power all devices. The battery module will be housed in the hand-held device. Along with a current rating (not to be exceeded), each battery has a nominal voltage that is assumed constant on a first-order design but actually declines over time as the cell is drained; this is one of the factors that explains the need for a voltage regulation circuit. By stacking consecutive battery cells in series, the overall array output voltage will be the individual cell voltage multiplied by the number of series cell connections. Adding parallel branches will proportionally increase the array's rated current output.

To properly size the battery array, it is necessary to have voltage rating and current consumption information for each component in the device. That information was extracted from selected component datasheets (more information on component selection can be found in later sections) and listed in the following table.

Component	Maximum Current Rating (mA)	Voltage Ratings (V)
Gyroscopes x2	7.8 (total)	2.375 – 3.46
Earbuds	10	0.447 – 1.736
ATmega328p Microprocessor	10	2.7 – 5.5
Ultrasonic Sensor	2	2.8 – 5.5

Table I. Component voltage and current ratings

The battery array was designed to approach the microprocessor and ultrasonic sensor's nominal voltage of 5 V. The most common commercial battery cells AA and AAA both supply 1.5 V. Three of these cells stacked in series gives a 4.5 V output voltage. The remaining 0.5 V is supplied by the voltage regulator (more information in next section). The gyroscopes will be powered by the ATmega328p's onboard 3.3 V supply and the earbuds will be driven with a stereo DAC module that will handle voltage modulation. Maximum power draw is overestimated using the simple equation of the sum of the products of maximum voltage and maximum current draw rating for each component. This computation yields 111 mW of maximum power draw which equates to roughly 25 mA from a 4.5 V stacked voltage array. This current draw is well within the rating of a single AAA battery cell. Using three AAA batteries stacked in series yields a worst case scenario of 40 operational hours (as analyzed from the data shown in Fig. 3) of use before the pack voltage drops too low to be properly regulated.

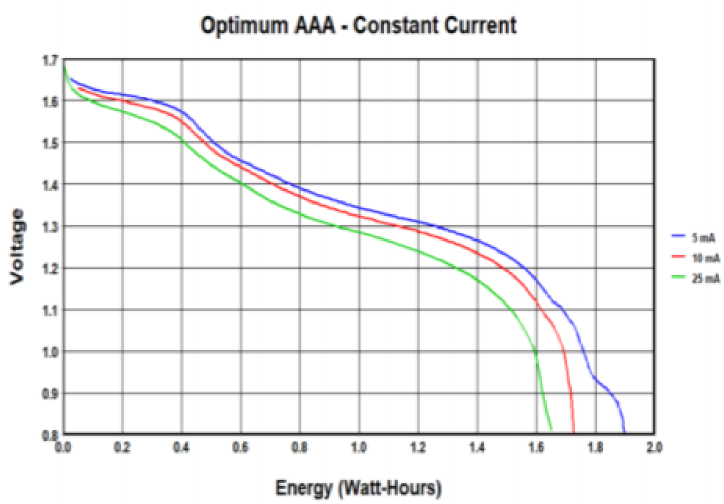

Fig. 3. AAA performance data [4]

Requirements	Verification
Pack provides sufficient voltage, 2.7-5 V	1. Assembly pack, 3 series AAA batteries. 2. Use voltmeter to probe output voltage. 3. Ensure voltage is within the specified range.
Pack can output sufficient current and power, 25 mA & 111 mW	1. Depending on the output voltage of the pack calculate a load resistance value that will draw 25 mA and a load resistance value that will draw 111 mW output power. 2. Load the battery pack with these resistances, using a single wattmeter to test voltage, current, and power flow. Ensure no drops in voltage or excessive heating in the batteries is experienced.

Table II. R&V for Battery Array

2.1.2 Voltage Regulation

As mentioned in the previous section, voltage regulation is required to maintain constant supply voltage for the components in the device. Not only is the battery array's output voltage not at the desired 5 V, but it also declines as the batteries are drained. For low power applications, such as this, there are two approaches typically used to regulate voltage: linear voltage regulation and non-linear/switch-mode DC-DC voltage regulation. The former has the advantages of simplicity and cost, but lacks in efficiency and also requires a stacked input voltage to be at least 2x that of the desired output voltage; it can only convert down voltage using a minority carrier transistor (thus lack in efficiency). The latter option is more complex and costly, but is also more efficient and can convert down or up voltage (buck-boost).

An integrated circuit (IC) switch-mode buck-boost voltage regulator was chosen for this application. The Linear Technology's LTC3204-5 has a fixed 5 V output and can handle input voltages of 2.7 - 5.25 V and is overrated for an output current of 150 mA. A circuit schematic for the typical application of the voltage converter was taken from the chip's datasheet and is shown in Figure . The chip will automatically shut off in under voltage situations which provides safety and battery health.

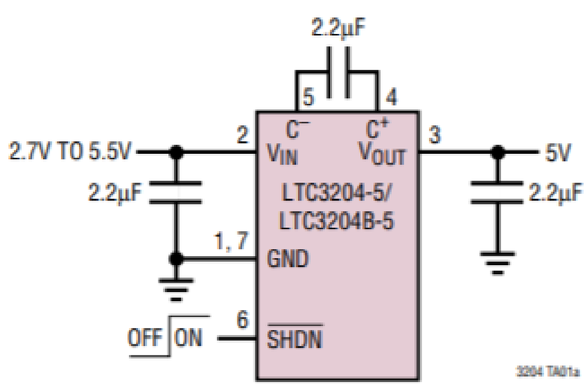

Fig. 4. Typical application of the LTC3204-5 [5]

Requirements	Verification
Regulator outputs 5 V for varying input voltages, 2.7-5.5 V	1. Assemble the circuit. 2. Using an Agilent voltage supply, sweep the input voltage from 2.7 V to 5.5 V while measuring the output voltage with a voltmeter. Set current limit to 30 mA. Check that V_o is 5 V.
Regulator can supply 22.5 mA	1. Applying a 220 Ω load resistance 4.5 V input voltage, measure load current with ammeter. Validate 22.5 mA output. 2. Ensure no drops in output voltage.
Regulator shuts off when input voltage is below 2.5 V	1. Apply a modest load of 300 Ω and slowly sweep the input voltage of a power supply from 4.5 V down to 2 V. 2. Watch output voltage with voltmeter and record input voltage at which the output voltage drops to 0 V.

Table III. R&V for Voltage Regulator

2.2 Distance Sensing

2.2.1 Ultrasonic Sensor

With the high-level requirement of general object sensing within 10 feet of the user, an ultrasonic sensor falls perfectly in this category. Compared to infrared and light sensors (outside of LIDAR), ultrasonic sensors have the longest range. They are slow (at roughly 20 Hz) but sufficiently fast enough for this application, and have low power consumption. Ultrasonic sensors transmit sonar waves and receive these back at the point of transmission, measuring time from transmit to receive. The acoustic media means that the reading is slow compared to EM and light based methods and also that the signal experiences dispersion at a significant angle. This angle affects the reading range and fidelity in aurally depicting the environment, however is advantageous in that the user cares about general objects in their path and not fine details that are impossible to discern from the hearing sense.

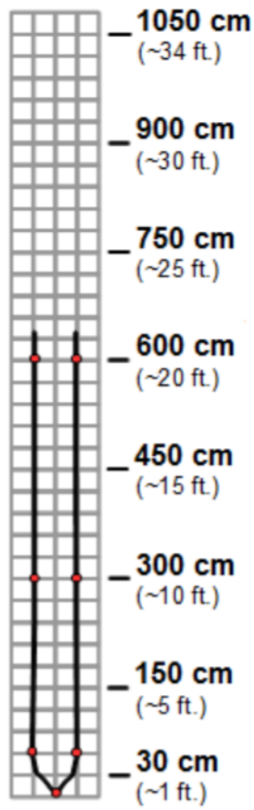

Fig. 5. LV-MaxSonar-EZ MB1030 distance reading capabilities on 30 cm grid [6]

A ultrasonic sensor that meets the required distance reading capabilities while maintaining a compact form factor was chosen (LV-MaxSonar-EZ MB1030). Its reading capabilities can be seen in Figure which was extracted from the components datasheet. After dispersion, the beam width is around 60 cm and can read up to 20 feet. Closer objects (within 2 feet) can be discerned with more detail.

Requirements	Verification
Accurately measure distances up to 20 ft away.	1. With a random object as a target, test the resolution of measurements at varying distances from 1 ft to 20 ft away. 2. Test solid angle by varying position of object against a long hallway and determining at what point the object is no longer detected.
Provide distance updates with a frequency of 20 Hz or greater.	1. Outputting to an Arduino, use the millis() function to time the period between distance updates from the ultrasonic sensor. Verify that this time is less than or equal to 50 ms.

Table IV. R&V for Ultrasonic Sensor

2.3 Feedback and Orientation

2.3.1 Gyroscopes

We will be using two MPU-6000's to determine the relative orientations of the handset and the headset. This device can connect to the Arduino microcontroller using an I2C connection, relying on a Master-Slave model. There are four pins, VDD, GND, SCL (Serial Clock), and SDA (Serial Data). Since we are relying on two gyroscopes that both need to send data to the microcontroller, one gyroscope will connect to the other gyroscope by I2C, which will then connect to the microcontroller by I2C. The MPU-6000 allows this configuration, forwarding the signals to and from the microcontroller to the other gyroscope. It determines this by the slave address the microcontroller specifies, which will differ by 1 bit depending on whether it wants to communicate with gyroscope 1 or 2. In Figure 6, the "Input from I2C master" will connect to the microcontroller, and "I2C output to the next device" will connect to the other gyroscope.

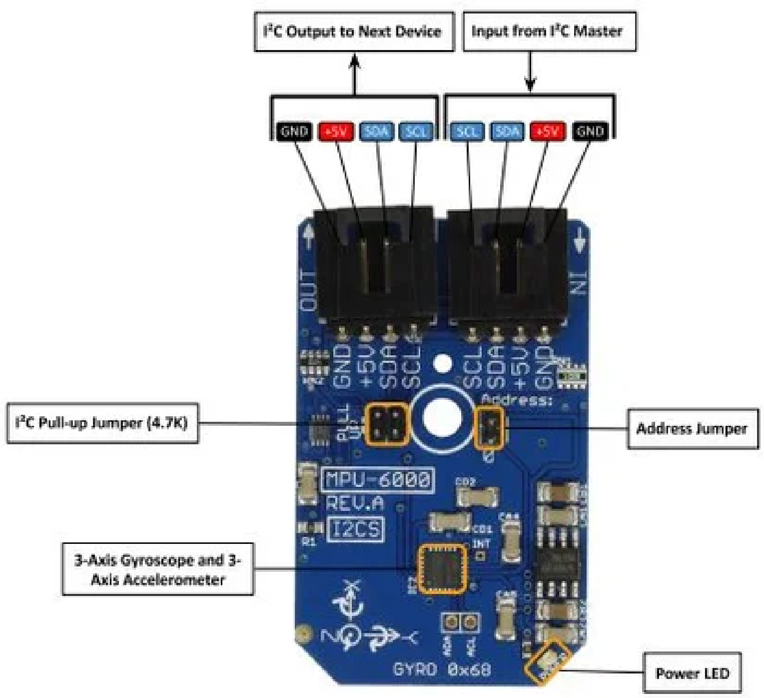

Fig. 6. MPU-6000 [7]

The gyroscope has registers which store the X, Y, and Z values of axis angles. As the documentation states, these values are 16-bit in size and can be sampled at any chosen value in the range of 4 to 8,000 Hz. We will set the sampling rate to be around that of the ultrasonic sensor. The maximum detectable speed of the sensor is programmable as well. The options are +/- 250, 500, 1000, and 2000 degrees per second. We will be going with the range of +/- 250 because it is within the expectations of a human's range of motion and choosing a lower number will maximize the fidelity of the sensor. Figure 7 below shows the physical representation of these values [8].

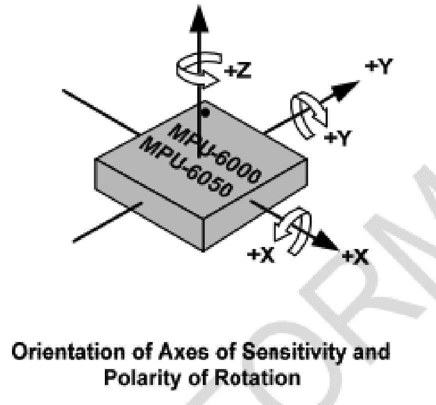

Fig. 7. Gyroscope Axis Depiction

Requirements	Verification
Provides accurate X, Y, and Z angular displacements from the user's headset and handheld device to the microcontroller.	1. Set up I2C connection from gyroscope to microcontroller and print out real time values to see if they match with expectations.
Gyroscope 2 connects to Gyroscope 1 as slave and can properly communicate with microcontroller.	1. Access the different device addresses from the microcontroller and ensure they are distinct and match expectations.

Table V - R&V for Gyroscopes

2.3.2 Earphones

Commercially available, cheap stereo in-ear earbuds are sufficient for this application. These earphones have a 3.7 mm headphone jack that will be used to transfer audio signals to the earphone drivers. To access the four ports on a 3.7 mm interface, a breakout board supplied by Sparkfun (BOB-1157) has a female headphone jack input and provides pin access to each ring on the headphone jack. A breakdown in [9] of Apple's wired earpods brings to light the electrical properties of a typical low end earbud. A driver impedance of roughly 100 Ω at audible frequencies and an average supply voltage of 1 V_{rms} results in current consumption of 10 mA.

Requirements	Verification
Earbuds correct loudness at a given driving voltage	1. Using a function generator, drive the earbuds by applying 1 V_{peak} sinusoidal waveform to the rings of the 3.7 mm headphone jack. Choose an audible frequency (440 Hz). 2. Lower the voltage to 0.5 V_{peak} and verify that the loudness is roughly half.

Table VI. R&V for Earbuds

2.4 Control, Software, and Auditory Feedback

2.4.1 Microcontroller

The microcontroller will be responsible for computing the distance of an obstacle from the ultrasonic sensor readings, finding the angle differential between the device and the user's head from the gyroscope sensors, and retrieving the appropriate 3D audio signal to play through stereo headphones.

The ATmega328P was determined to be the processor of choice for the control unit due to its ease of use, prevalence, and the designers predisposition to the Arduino platform which uses this chip. Moreover, the ATmega328P has 14 I/O pins which is more than enough to receive inputs from our gyroscope and ultrasonic sensors and send an audio output through a DAC to our headphones. The ATmega328P, like most microcontrollers, has very limited SRAM space (only 2 kilobytes). However, it is compatible with SD Card reader modules which will enable the microcontroller to easily access stored audio files during runtime [10].

Requirements	Verification
Easily programmable	1. Solder chip holder onto PCB. 2. Program ATmega328p chip from an Arduino using the micro USB cable, extract the chip and place it onto the PCB.
Chip outputs 5 V on all GPIO pins	1. Write to GPIO pins and check pin voltage with a Voltmeter to compare to expected output.
Chip can produce stereo audio.	1. Send two pure tones with different frequencies to the DAC and check if both tones are audible through headphones.

Table VII. R&V for Microcontroller

2.4.2 3D Audio Generation

The 3D audio feedback will create an effect that causes the user to perceive the source of the signal to be aligned with the position of the obstacle. A 3D audio signal can be generated by convolving an input sound with a pair of head-related impulse responses (HRIR), a filter that characterizes how a sound wave reaches each ear from a point source [11].

We plan to first obtain a collection of filters consisting of several HRIR pairs corresponding to a large array of different positions (various pairs of horizontal and vertical angles) around the user. The vertical angles will range from 0 to 180 degrees while the horizontal angles wil range from 0 to 360 degrees. Due to limited storage, we will sample both of the angles in 10 degree increments resulting in a total of 648 possible positions and filter pairs.

We will then generate a sine wave with a frequency of 880 Hz for about 10000 samples (corresponding to about .25 seconds at the standard sampling rate of 44.1kHz). We will apply each of the filter pairs on the signal, resulting in a total of 1296 different audio signals. Assuming we use 8-bit audio, the collection of audio signals will take about 12.9 megabytes (calculation shown below).

$$1\,bytes\;*\;10{,}000\;samples\;*\;1{,}296\;filters = 12{,}960{,}000\;bytes$$

At runtime, the microcontroller will compute the horizontal and vertical angles relative to the user's head and the closest matching 3D audio signal will be retrieved from the SD card to be played through the headphones. The audio signals will be generated offline, using a high level programming language such as Python.

Requirements	Verification
The source of the audio should appear to originate at roughly the correct position relative to the user's head.	1. Generate a 120 second long tone of about 880 Hz 2. Divide the signal evenly into 648 segments (corresponding to each filter pair) 3. Sweep through the horizontal angles at fixed vertical angles by applying the appropriate HRIR pairs to each segment of the pure tone 4. Verify that the source of the audio signal appears to rotating around the user at different elevations by playing the filtered tone through stereo headphones.

Table VIII. R&V for 3D Audio Feedback

2.4.3 Micro SD Card Reader

Due to the high volume of audio files we plan to store and the limited SRAM storage on most microcontrollers, a 2GB SD card is necessary. To enable our microcontroller to access the SD card, we will use a Memory Card Shield Module with a SPI Reader Micro SD Memory Card (shown below). This module is compact (4.1x 2.4cm) and is compatible with the Atmega328p microcontroller [12].

Fig. 8. SPI Card Reader Shield

Requirements	Verification
The SPI card should be able to transfer data from an SD card to the microcontroller as needed.	1. Save an arbitrary array to the SD card 2. Load script to access SD card and print the data to the serial monitor on the microcontroller 3. Verify that the serial output matches the data originally saved on the SD card.

Table IX. R&V for SD Card Reader

3 Tolerance Analysis

To quantify the accuracy of this device, it is useful to calculate the solid angle subtended by a perceived object at 10 ft from the user (distance specified in the high-level requirements). In other words, what is the field of view covered by the ultrasonic beam at 10 ft? Fig. shows the beam pattern of the acquired ultrasonic sensor. It can be seen that the beam width is 60 cm at 20 ft, corresponding to an effective covered area of:

$$\pi r^2 = \pi(0.3)^2 = 0.28\ m^2$$

This is compared to the total surface area of a sphere with radius 10 ft (304.8 cm).

$$4\pi r^2 = 4\pi(3.048)^2 = 116.75 m^2$$

Thus, if the user is holding their device fixed in a single position, they will have information about roughly 0.2% of their environment at 20 ft, compared to 1% at 10 ft. Clearly, there is a trade-off here between fidelity and awareness of the environment. For example, the user will be able to discern smaller details in their perspective at 20 ft than at 10 ft, but their awareness of other objects at that distance is diminished. At 10 ft, the user may be aware of more of their environment in each instant, but will not be able to discern such small details. To compensate, the user will have to vary the frequency of their sweeps. Additionally, this behaviour is somewhat intuitive and therefore we expect the user will mentally adapt within a short timespan.

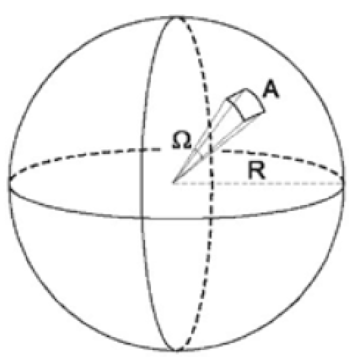

Fig. 9. Solid angle graphical depiction [13]

4 Differences in Solution Approach

4.1 Overview

A solution proposed and completed in the Spring 2017 semester took a different approach to solve the problem of environment navigation for the visually impaired. That solution involved a series of ultrasonic sensors placed around a belt that the user would wear. The belt would provide haptic (vibrational) feedback based on the distances read by each sensor. However, this proposed solution has a few shortcomings that we aim to address in our approach.

First of all, the previous design utilizes 8 ultrasonic sensors and 8 eccentric rotating mass (ERM) actuators which is not cost effective, and requires a substantial amount of power. Our approach improves this aspect of the design by utilizing fewer sensors (2 gyroscope sensors and 1 ultrasonic sensor) and a far more energy efficient feedback system. Based on the analysis shown in Section 5, the bulk cost of our device is about 70% of that of the previous design.

Furthermore, the motion sensors are stationary in the previous design, resulting in blind spots that the sensors will not be able to detect. The approach uses only 8 sensors, which is insufficient to sample the entire radius around the user. This wearable device method also makes the assumption that all encountered obstacles are roughly around the user's waist level, which will likely not hold in practice. We address these issues by giving the user the ability to control the direction of the sensor through a handheld device. This will ensure that the user can sample the full radius and vary the elevation of the device, in a manner that is as intuitive as using a flashlight.

A similar blind spot related issue arises in the wearable device's feedback system. Since there are only 8 haptic sensors, the user can only perceive 8 different locations with no information about the elevation of a given obstacle. We address this issue by using the 3D audio feedback system, which allows us to densely sample the area around the user.

4.2 Comparative Design Analysis

Based on the datasheet [14], the HC-SR04 ultrasonic sensor (used in the wearable device approach) has a measuring angle of approximately 30°. The beam angle is shown in the context of the wearable device in the figure below.

In the best case scenario (assuming no overlap between the measuring angles of the sensors), the 8 sensors will cover only 67% of the total area around the user. Since the sensors are not uniformly placed, over a third of the total area around the user cannot be observed. In order to detect an obstacle in one of the device's blind spots, the user must rotate his or her entire body.

Though the single ultrasonic sensor outlined in our solution has a far smaller field of view at a given instance, the user may sweep the device in the direction they are moving in (similar to how white canes are used) and eliminate the existence of any blind spots.

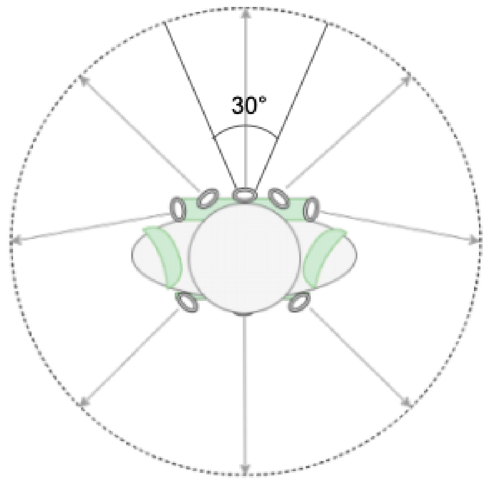

Fig. 10. A figure taken from the original wearable device design document

The vertical field of view is particularly limited since all of the sensors are placed at the same elevation in the wearable device. We compute the maximum vertical field of view (at the maximum distance away from the sensor) based on the figure below.

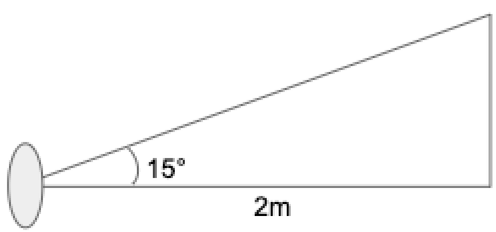

Fig. 11. Beam angle diagram

To compute the vertical distance, we simply use the following equation:

$$y = 2tan(15°) \approx 0.536m$$

In other words, the wearable belt can only detect objects around 54 centimeters below or above waist level. Since our device detects an object in whichever direction the user points it towards, our approach is not limited to only certain elevations.

5 Cost Analysis and Schedule

With an assumed hourly rate of $50 for three part-time designers working 20hrs/week, the total design and development personnel cost for the entirety of the 10 week development period is approximately:

$$3 \cdot \frac{\$50}{hr} \cdot \frac{20hrs}{wk} \cdot 10wks \cdot 2.5 = \$75{,}000$$

Material and component cost estimates are provided in the table below and both individual and bulk costs are included:

Component	Prototype Cost ($)	Bulk Cost ($)
Microprocessor (ATmega328p extracted from Arduino for programming)	18.00	1.73 (standalone chip)
Ultrasonic Sensor (LV-MaxSonar-EZ)	29.95	25.00
Gyroscopes x2 (InvenSense MPU-6000)	26.00 (total)	17.50
Voltage Regulator (LTC3204-5)	4.00	2.50
Batteries x3 (Duracell AAA)	4.50	3.00
PCB (PCBway est.)	5 for 5 (min.)	0.77 per PCB
Earbuds (Verbatim Stereo CDW	3.00	2.50
Earbud Breakout (Sparkfun BOB-1157)	4.00	2.00
SPI Card Reader	5.50	4.00
Stereo DAC	4.76	2.00
On-off Toggle Button (Judco 40-4526-00)	1.64	1.00
PCB Components (Capacitors, connectors, diodes) est.	3.00	1.00
Casing	10.00 (3D printed)	10.00 (stamped w/ acrylic)
Total	**119.35**	**73.00**

Table X. Material cost breakdown

Including development and design costs as well as prototype materials costs the device will price out at: $75,113.85. This number will decrease per unit as the device is produced in bulk.
To successfully carry out the design and prototyping of this product by the end of the semester, a tight schedule must be adhered to. The following week-by-week schedule has been developed to keep the designers on track.

Week	Arnav	Darius	Noah
1	Code 3D audio generator and DAC communication.	Code I2C for gyroscope communication and data extraction. Order components.	Put together circuit schematic and PCB layout. Design CAD for the handheld device.
2	Write out microcontroller code for general case handling and flow between components.	Test gyroscope calibration and fix gyro 2 to the earphones.	Assemble PCB and 3D print the flashlight.
3	Audio testing and debugging.	Orientation and general component testing and debugging.	Circuit debugging and full assembly for a comprehensive preliminary test.
4	Write a final report, demo, and present results.	Write a final report, demo, and present results.	Write a final report, demo, and present results.

6 Ethics and Safety

Since the device we propose is intended to be used as a primary source of navigation, malfunctions in the device could seriously harm the user. As such, thorough testing of the object sensors and the audio feedback system is necessary in order to ensure that the device never fails to detect the presence of an object and provides accurate feedback to the user. It is paramount for us to be forthcoming about any potential bugs or limitations in the device to make sure that our product will not result in any injuries, in accordance with Rules #3 and #9 in the IEEE Code of Ethics [15].

Safety risks involved in the designed product can be incredibly consequential. If the device doesn't correctly identify an object in close proximity to the user, that object has serious potential to harm the user. One method of risk mitigation is through the use of an ultrasonic sensor as the main sensor. This type of sensor has a large beam angle compared to other types of proximity sensors (infrared, LIDAR, etc.) and therefore gives a buffer for the user to identify all objects incident upon that beam. The tighter the beam angle, the more the user has to sweep the device to get a reading and consequently the more likely they are to miss a fine detail that may pose danger to the user.

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