# Blindsight: Proximity Sensing and Wireless Haptic Feedback

A Major Qualifying Project

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree in Bachelor of Science

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# Blindsight Assistive Technology

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April 24, 2019

# Abstract

A staggering 98 percent of blind people have experienced head-level accidents with some requiring professional medical assistance. Current technologies such as the white cane and guide dogs come with a significant flaw: the inability to detect objects at head-level. As such, the objective of this project was to create a more effective and affordable means to detect and prevent head-level injuries in blind people. Blindsight uses ultrasonic sensors to detect obstacles and transmits this information to haptic vibration motors which will then alert the user of incoming obstacles.

## Acknowledgements

The completion of our project would not have been accomplished without the sponsorship of the New England Center for Analog and Mixed Signal Integrated Circuit Design (NECAMSID) lab.

We would also like to thank Sharon Strzalkowski and the Commission of the Blind for their aid during the testing phase. The feedback received was beneficial towards making better prototypes.

Additionally, we would also like to extend our sincerest thanks to our Major Qualifying Project advisors, Professor Stephen Bitar and Professor Yitzhak Mendelson for their constant support, patience, and guidance throughout the duration of this project.

# Executive Summary

According to the World Health Organization, there are approximately 1.3 billion people around the world living with some form of vision impairment. Out of these 1.3 billion, about 217 million have moderate to severe vision impairment and 36 million people are entirely blind (*Blindness Statistics*, 2018). The number of people with legal blindness is only expected to increase as the population ages. Any significant loss of sight is life-altering as significant adjustments must be made in order to maintain the same level of mobility. Daily activities and tasks such as cooking and navigating in tight spaces, can become extremely challenging and potentially dangerous (*Visual Impairment*, 2016).

As such, there has been a greater demand for assistive devices for navigation and orientation. The most common navigation tools used today are the guide dog and the white cane. However, these tools come with a significant flaw: the inability to consistently detect objects above the waist. According to a study done in the University of Santa Cruz, 98 percent of blind respondents have experienced head-level accidents with some requiring professional medical assistance (Manduchi & Kurniawan, 2011). About 26 percent of the time, this caused the respondent to doubt their ability to travel alone. Already, innovations such as the Sunu Band and the Ultracane have become available to the public to help with this issue; however, these products are often times not affordable for a blind user (Manduchi & Kurniawan, 2011).

To combat this issue, our team developed a device that aims to aid blind individuals in detecting head-level objects. The system comprises of a sensing module in the form of a pair of glasses and two haptic feedback modules in the form of wristbands. The glasses collect proximity data from the environment and transmit this data wirelessly to the bands. The bands then pulse at different intensities to alert the user of any head-level objects in their path.

The seven principles of universal design were applied to create a system that tended to the needs of a wide customer base within the blind community. This was done by first researching assistive technology and blindness, defining customer needs and design constraints, reviewing previous research, and assessing prior art. Next, value analyses were carried out in order to assess and determine which components to include. Factors such as performance, affordability, reliability, ease of use, and design were taken into account when judging different components.

The chosen components were then used in order to create both the glasses, which included the sensors, and the haptic feedback bands, which included the vibrating motors. Wireless communication was established between the glasses and the bands and power consumption was determined under continuous transmission and vibration conditions. Later on, the team began prototyping on a circuit board with which initial component verification and functional testing was conducted. Once the components were better understood, the design was reevaluated, and unnecessary parts were eliminated.

Communication between the microcontroller and the bands was then established and tested. The initial prototype was finished within the first few weeks of January. Following this, the team met with Sharon Strzalkowski, the Regional Director of the Worcester Commission of the Blind, to test the prototype and receive feedback. Using the feedback received from the meeting, modifications were made in the design and a PCB was created in order to fit all of the components into a sleek, compact design.

Further testing was carried out on individuals with no visual impairment. These individuals were asked to walk through a course with obstacles that were meant to simulate the dangers present in common environments that might cause head-level accidents to occur. The feedback received was informative in multiple areas. Firstly, it was clear that there are challenges in effectively communicating information through vibrations. More specifically, a trade-off exists between the periodicity of vibrations and the intensity of vibrations. Another area of weakness that was identified through feedback was the characteristics of the ultrasonic sensor that was used. Participants complained about a narrow field-of-view and as designers we also noticed the effects of an inadequately low sampling rate on the speed with which the presence of obstacles was detected.

Although the device that was produced at the end of this project was not perfect, the most important takeaway from this experience was the importance of using a design centric approach in the development of disability aids. It was noticed that disability aids tend to sacrifice aesthetics and functional design in order to tackle the problem. Even though the resulting device may solve the problem for which it was designed, the device will most likely suffer from low adoption rates and high abandonment rates. This is the result of the stigma attached to disability aids that stand out and have no aesthetic attractive to make the user proud of wearing the device rather than ashamed. It is then crucial to have the Seven Principles of Universal Design at the core of the development of the device rather than to develop a device first and then attempt to adapt it to meet these principles. Blindsight was developed in this manner, with a very clear design philosophy and constraints pandering to the needs of blind individuals from the start of the project. Wireless communication, wireless charging, modular design, improved sensors and a sleek casing were the result of this design centric approach and these are some of the features that distinguish Blindsight from other products on the market.

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# 1 Literature Review

## 1.1 Introduction

There are more than 25.5 million people living with some sort of vision impairment in the United States with 1.1 million being completely blind (*Blindness Statistics*, 2018). These numbers are only expected to rise as the population ages. In fact, according to the National Eye Institute, the number of people with legal blindness will increase by 21 percent each decade reaching a staggering 2 million by 2050 (*Visual Impairment*, 2016).

Any significant loss of sight is traumatic and life-altering affecting not only the quality of life, but also the probability of accidental injury. Routine tasks and daily activities that most of us take for granted, such as crossing the road, cooking, or navigating in tight spaces, can become extremely challenging and overwhelming for someone trying to navigate using only four out of five senses.

As such, the need for assistive devices for navigation and orientation has increased. The most common and affordable navigation tools used today are guide dogs and the white cane. Despite their popularity, they cannot provide all the information needed for safe mobility since the cane does not detect anything above the waist and the guide dog is concentrated mostly on objects at its own height. According to a study done in the University of Santa Cruz, 98 percent of blind respondents have experience head-level accidents with 23 percent of accidents requiring professional medical assistance. After these incidents, in 26 percent of the cases, the head-level accident affected the respondent's confidence as an independent traveller (Manduchi & Kurniawan, 2011).

To combat this issue, this project applies the principles of universal design to develop a device that seamlessly integrates into the life of the individual, while solving the clear path problem. The Blindsight Assistive Technology uses ultrasonic sensors integrated into the frame of the glasses to detect obstacles above the waist level. The presence of obstacles within the Field of View (FOV) is communicated via two or more vibrating motors. The simple, attractive, and inclusive design allows for the device to be easily adopted by visually impaired individuals regardless of age, gender and level of dexterity.

## 1.2 Problem Statement

The most popular assistive technologies, the white cane and the guide dog, do not offer any form of consistent feedback regarding the presence of obstacles above the waist level. Existing solutions to the problem tend to disregard the principles of universal and aesthetically pleasing design leading to low device adoption rates and device abandonment. The challenge is to design a device that is capable of solving the clear path problem, seamlessly integrate into the individual's life, and accommodate for any level of dexterity.

## 1.3 Competing Products

Since the 1970s, many groups have designed devices aimed at improving the quality of life of blind individuals with mixed success. Understanding the successes and failures of these products is crucial to developing a product capable of competing in the current assistive device market. Therefore, a brief history of the development of blind assistive device is given below such that the reader can become familiar with how the technology started and where it is today. The devices described were obtained exclusively from patents and are listed in a chronological manner.

### 1.3.1 Prior Art

- Highly Relevant: Patents that are in direct conflict with the idea of the Blindsight device.
- Relevant: Patents that have some relevance to the project, but are not in direct conflict with it.
- Irrelevant: Patents that are listed because they form part of a group of patents filed to complement a highly relevant patent but may hold little value for the project.

***Obstacle Detection System Using Sensors on Goggles (1972):***
This patent, one of the first filed for a wearable blind assistive device technology, was approved in 1972 and has since expired. In this patent, the inventor describes the use of light based time-of-flight ranging sensors to detect obstacles in the path of the user. These sensors are mounted on a pair of goggles behind the lens (Benjamin, 1970).

The main takeaway from this patent is the form factor that is functionally efficient while simultaneously being aesthetically pleasing. However, there are some negative aspects of this design including the location of the battery pack that runs a wire to the glasses to power the device. In any potential device resulting from this report, the power system will be located on the device itself rather than in a separate unit connected by a wire.

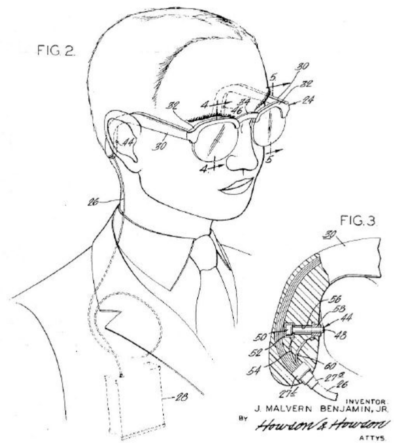


Figure 1: Object detection sensor goggles image filed with patent

***Systems and methods providing tactile guidance using sensory supplementation:***
This patent describes a device that uses a vibrating actuator to guide a user to a desired destination through GPS. The use of vibrational cues allows the user to concentrate on the visual and auditory feedback rather than to focus on a device to follow directions. This patent simply describes a method for waypoint finding, not a device for obstacle avoidance. However, the use of tactile feedback rather than auditory feedback for directional cues is a notable characteristic that will be incorporated into the device resulting from this paper (Sokoler, Nelson, & Pedersen, 1999).

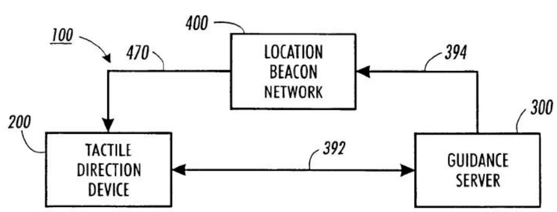


Figure 2: Software algorithm flow diagram image filed with patent

***Ultracane Patent:***
This patent was filed by Sound Foresight, the company that produced the Ultracane, however, the description of the device found in the patent document and the description found on the Ultracane product website differ greatly. The most likely reason for this discrepancy is that the patent was filed at a very early stage of development for this device and therefore

the final product design varied greatly while the technology that was patented remained the same (Withington, Waters, Povey, & Hoyle, 1998).

The Ultracane is a device that that includes a number of ultrasonic ranging sensors that provide the user with increased spatial awareness through tactile feedback. From a systems level perspective, a potential device developed as a part of this paper would also use a ranging sensor and provide proximity information through haptic feedback. One of the disadvantages of the ultracane is the location of the sensor below the hip which might decrease the device's field of view. Another drawback related to the location of the device is the motion artifact which is ever present due to the placement of the device on the cane which is constantly moved by blind individuals. This continuous motion might cause the proximity information to be more inaccurate than if the sensor were attached to a more stationary part of the body (e.g. head, torso etc.).

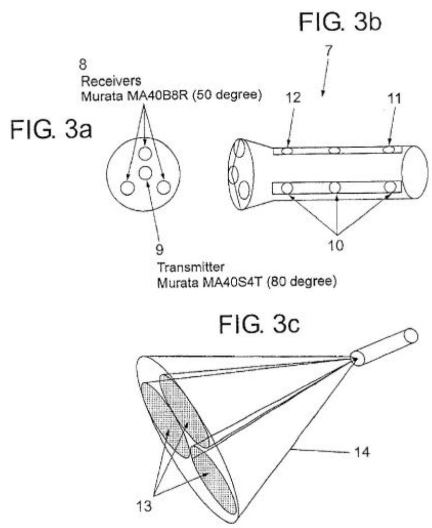


Figure 3: Ultracane image filed with patent

***UAV Obstacle Detection and Avoidance (Stereovision):***

This patent describes the use of a stereovision setup to capture images that will then be sampled to obtain a 3D representation of the space. The distance between the points in the space and the drone is calculated based on the latency between transmitted and received signals. The trajectory of the obstacles is predicted in order to execute corrective actions. The advantages of this device is the accuracy of the sensor module and the detailed 3D information gathered by the device. However, the haptic feedback module required to communicate this detailed 3D information to the user would have to be equally complicated which would not only hinder the intuitive design this paper is aiming for but would also increase cost, power consumption and size as a result (Nichani, 1999).

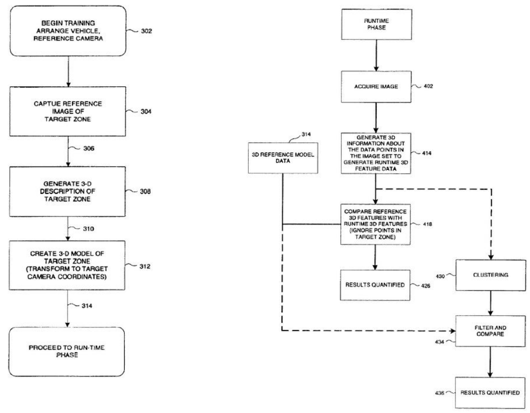


Figure 4: Software obstacle avoidance algorithm flow chart

***Sensory Substitution Through Vibrating Actuators:***

This patent describes a sensory substitution device that captures depth and color information about the environment. This information is relayed to the user via vibrating actuators. In respect to our project, the characteristic of this device that is of most interest is the haptic feedback module which transmits depth information via intensity and color information via frequency. The patent does not cover how this information is collected. Rather, it focuses on the signal processing aspect once the information has been received (Ward, 2005).

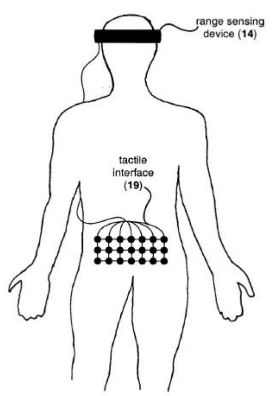


Figure 5: Sensory Substitution device image filed with patent

***Object Detection System Using Sensors on Goggles with Gigahertz Waves:***

This patent describes a pair of goggles that achieve obstacle detection using a 94GHz wave transceiver very similar to the sensor technology that will be utilized in a potential device resulting from this paper. Despite the accuracy of the sensor module and the apt location of the device, there are many drawbacks to this product. For one, the obstacle information is relayed to the user via audible signals which would interfere with the blind individuals ability to listen to feedback from their surroundings. Additionally, the 3x7 tactile matrix displayed in the figure would result in complex vibrational cues that might prove to be less effective than simple vibrational feedback (Jung, Chae, & Rhee, 2006).

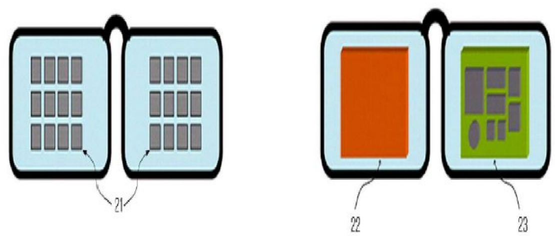


Figure 6: High frequency goggle object detection device image filed with patent

***Electronic Travel Aid (ETA) Using Multiple Infrared Rangefinders:***

This patent describes an ETA that uses multiple infrared rangefinders to guide the user around the environment. The distance information is relayed to the user via audible or vibrating signals, each one unique to each direction. This device scores well in accuracy and power consumption categories in indoor settings due to its simple design. However, it suffers outdoors given the background infrared interference present in the environment due to the sun (Amedi & Hanassy, 2010).

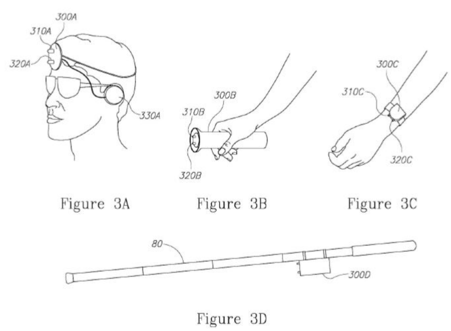


Figure 7: ETA device image filed with patent

***Project BLAID Blind Navigation Assistance Device:***

US20160225287A1: Describes the use of sensors to identify objects in the scene and to communicate their presence to the user via some actuator. This is a very broad statement that seems to encompass the entirety of time-of-flight assistive device that communicate via haptic feedback (Djugash, 2015).

US20160225286A1: A navigation aid that uses a number of cameras and image processing to identify objects in the scene. Information about the object is relayed to the user via sound (Dayal, Chen, & Thackston, 2016).

US20180012377A1: Describes another calibration method of the camera (?, ?).

US20170367921A1: Describes the method of correcting the image captured by the camera with inertial sensor. This negative feedback corrects image tilt in order to properly process the scene for object recognition (Matsuno, 2016).

US20180012376A1: Describes a method for aligning the cameras with the physical characteristics of the user. This is something to take into consideration in designing the a potential device for this paper given that a general configuration may not fit all users (Dayal et al., 2016).

The BLAID device using a conjunction of sensors and cameras to provide a 3D visualization of the environment. Despite the impressive engineering behind such a complex product, the BLAID device tries to do too much in a single unit. The device integrates AI image processing, advanced sensor obstacle avoidance, tactile feedback as well as auditory feedback. All these different characteristics can make the use of this device difficult and non-intuitive.

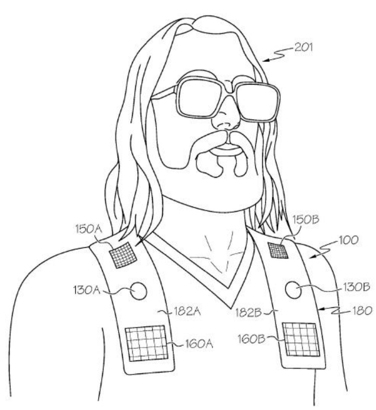


Figure 8: BLAID image filed with patent

***Electronic Travel Aid on a Necklace:***

This patent describes an electronic travel assistance device that is worn around the neck. The necklace includes vibrating actuators that will communicate the presence of objects as detected by the imaging sensors. The vibrations are felt on the neck of the user as shown in the figure. The location and simplicity of the haptic feedback module are attractive features. However, the location and vulnerability to movement when walking are characteristics that will not be mimicked for any potential product developed (Mahoney, 2009).

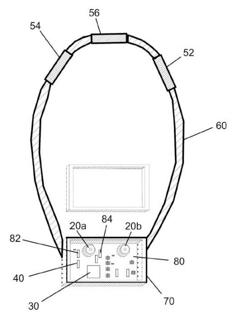


Figure 9: ETA device image filed with patent

***UAV Obstacle Detection and Avoidance (Monovision):***

This patent describes apparatuses and methods for detecting an obstacle in a path of an Unmanned Aerial Vehicle (UAV) including, but not limited to, data received from a single image/video capturing device of the UAV, a score computed based on the received data, and at least one obstacle avoidance maneuver performed based on the score. The sensor accuracy of this device is very impressive. However, due to the large difference in application this device does not provide a model for the development of a potential device in terms of power consumption and aesthetic design (Kanade, Sweet, & Gehlhaar, 2016).

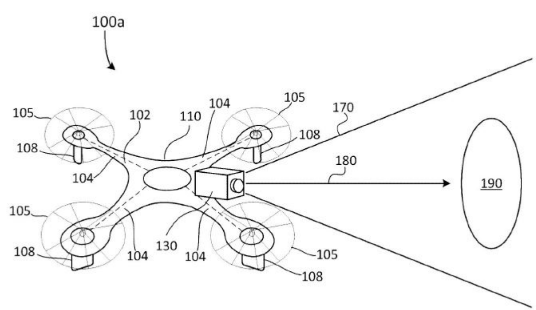


Figure 10: Artist rendition of quadcopter with monovision sensor mounted on front

### 1.3.2 Competitive Value Analysis

Table 1: Value Analysis for Competing Products

| | Sunu Band | | BuzzClip | | UltraCane | | iGlasses | | Tom Pouce | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Considerations* | Weight | Score | Weight | Score | Weight | Score | Weight | Score | Weight | Score |
| **Reliability (100)** | 7 | 700 | 6 | 600 | 10 | 1000 | 6 | 600 | 5 | 500 |
| **Design (65)** | 8 | 520 | 7 | 455 | 9 | 585 | 1 | 65 | 1 | 65 |
| **Ease of Use (50)** | 8 | 400 | 10 | 500 | 10 | 500 | 10 | 500 | 9 | 450 |
| **Performance (40)** | 7 | 280 | 6 | 240 | 9 | 360 | 5 | 200 | 6 | 240 |
| **Affordability (25)** | 5 | 125 | 7 | 175 | 2 | 50 | 8 | 200 | 10 | 250 |
| **TOTAL** | | 2025 | | 1970 | | 2495 | | 1565 | | 1505 |

As of now, few products with similar goals are offered in the market. We chose five competitors who had similar goals to ours in order to fully understand what appealed to the market. These included the Sunu Band, BuzzClip, UltraCane, iGlasses, and Tom Pouce. All of these products aimed to improve the quality of life of blind individuals by providing a means for self-navigation that would prevent possible injuries. The main differences of these products were the design as some took the shape of a clip while others took on more traditional shapes like a cane.

To further evaluate our competition, the customer's essential criteria was divided into reliability, design, ease of use, performance, and affordability. A brief explanation of each is shown below. Each of these categories were rated from a scale of 1-10. Additionally, a small description of each product is included.

- Reliability: Accuracy, Response time
- Design: Durability, Acceptable aesthetic design, Modularity
- Ease of Use: Intuitive to use, Comfort
- Performance: Battery life
- Affordability: Price per unit

As shown in the value analysis, the competitors that come on top are the Ultra Cane and the Sunu Band at 2495 and 2025 points respectively. Therefore, our product will try to replicate the most successful aspects of these competitors and attempt to negate their cons.

**Sunu Band:**
Sunu Band is one of the more popular products offered in the market today. The Sunu Band uses both radar and augmented reality to enable people who are low vision and blind to travel without assistance. Advanced haptic feedback is used to guide the user around obstacles and navigation sensors connect the user to the world around them.

Figure 11: Sunu Band

The band uses echolocation/sonar to detect objects up to 5.5 meters (16 ft) away. Haptic feedback is used to then inform the user on how close they are to potential obstacles. This product complements the cane or guide dog. Furthermore, it retails for $299 and comes equipped with a haptic compass, place finder/explorer and GPS navigation app. The Sunu Band's battery has an expected life of up to three days of average usage, 5 - 8 hours on constant use, or seven days on Low Power Mode (Sunu, n.d.).

**Buzzclip:**
The BuzzClip is a discreet wearable developed by iMerciv for blind people. The device uses ultrasound to detect obstacles and then notifies the user of obstacles through haptic feedback. It offers head level obstacle detection and can be attached in multiple places. As seen in the image below, the BuzzClip can be attached in different areas due to its shape and clip which add significant variability to its use.

Figure 12: BuzzClip

The BuzzClip has two selectable ranges: a 1 meter and a 2 meter range. Additionally, the battery is able to last up to 10 hours throughout day-to-day use. The battery level is indicated to the users through vibrations when turned on. This device retails for $249 which puts it in a similar price range as the Sunu Band despite having less features (iMerciv, n.d.).

**Ultracane:**

The UltraCane uses "narrow beam technology" to detect obstacles within 2 or 4 meters using ultrasonic waves from two sensors. The user is then given tactile feedback through two vibrating buttons on the handle over which the user places their thumb. These buttons, when vibrating, are able to indicate the direction of the obstacle and the proximity of the obstacle by the frequency of the vibration. This way, the user is able to have a rough idea of the layout of their immediate environment. However, this product is not without its cons.

Figure 13: UltraCane

The UltraCane is powered using AA batteries and as such need to be replaced. Additionally, this product is definitely the most expensive at roughly $800 per cane (Sound Foresight, n.d.).

**iGlasses:**

The iGlasses Ultrasonic Mobility Aid looks like an ordinary pair of glasses. Objects in the path are detected via ultrasonic sensors and communicated through vibrations, similarly to the other products. Furthermore, it is extremely easy to use and a series of beeps will alert the user of the current battery level.

The vibration intensity level and arms of the glasses can be adjusted depending on the user's preferences. Furthermore, it has a battery life of around one weak of typical use (10 hours of continuous vibration) and is rechargeable via a AC charger. This is one of the cheaper options at only $96.10 (Ambutech, n.d.).

**Tom Pouce:**


Figure 14: iGlasses

The TOM POUCE is a discreet, removable device which attaches to the cane and transforms it into an electronic cane. Its purpose is as an obstacle-reader that detects obstacles up to 2m high and between 2 - 15m ahead (Farcy et al., 2019).

Figure 15: Tom Pouce Electronic Canes

However, this product seems to only be offered in France and it is unknown if it will be available in the USA. This device is available to users free of charge, once the user has received a 30 hour training by one of Visoptronic's centres.

## 1.4 Complementary Products

### 1.4.1 The Long Cane

The long cane is the most popular assistive technology (AT) for the blind and visually impaired. Although government programs in the United States provide long canes for free to blind individuals following a short training period, approximately only 10% of the estimated 1.3 million blind individuals own a long cane. Research shows that one third of cane users are above the age of 65, while two thirds of visually impaired people are in the same age category (*Blindness Statistics*, 2018). This suggests that the difficulty in training as well as the additional requirements of older individuals combine to contribute to the limited adoption of the cane. Furthermore, the association between the cane and disability is a source of social stigma that is recognized as a contributing factor to its low adoption rate.

Among its users, the simplicity in its design is a major factor in its success. The cane is typically composed of a number of cylindrical segments with an elastic running through their interior. This design allows for the cane to be folded by pulling the segments apart. The cane is used to sense objects in the immediate vicinity of the user, to provide feedback regarding the type of terrain, and to signal that the user is blind. Limited customizability of the cane allows for the cane to be adapted to different terrains. The following grasps and techniques, applied in the correct situations, allow the user to navigate more safely. The way the cane is used is an important consideration in the development of a complimentary technology as the movements performed by the user may justify particular designs.

***Types of Long Cane Grasps:***

1. Handshake Grasp: The cane is held by the dominant hand as if the user were to give a handshake and such that the grip extends one to two inches past the wrist joint. The index finger is extended and placed flat along the cane with the rest of the fingers curled around the cane. The arm holding the cane is fully extended next to the body. Holding the cane in this manner allows the cane to safely slide past the users hand without impacting the body if it gets stuck on a crack. This relaxed position is also less tiring as the arm is held loosely alongside the body.

2. Overhand Grasp: The cane is held with the thumb facing the floor and extended flat along the cane. The rest of the fingers are curled around the cane.

3. Pencil Grasp: The cane is held like a pencil, with the weight supported by the middle finger and the web of the thumb and index finger. The palm of the hand is faces inwards.

***Travel techniques with the long cane:***

1. Diagonal Trail Technique: This technique is used to navigate familiar spaces where there are no changes in elevation and few obstacles. The cane is held, using the handshake grasp, diagonally across the body while trailing the floor line. Since the cane is held

across the body, it allows the user to detect any obstacles below the waist line. It is important that this technique is used in familiar environments because the position of the cane does not inform the user of the presence of any obstacles above the waistline (Terlau Rosanne, n.d.).

2. Two Touch Technique: This is the most common travel technique and is used to travel without an edge for reference. The taps are made opposite to the leading foot such as to anticipate an obstacle in the path of the upcoming foot. The taps occur about an inch past the shoulder and the arc made by the cane as it travels from one side to the other should not exceed an inch (Terlau Rosanne, n.d.).

3. Touch and Drag: This technique is used to follow a raised edge, which provides a straight path, and to locate obstacles on the path. The motion begins with a tap away from the raised edge about an inch past the shoulder and finishes at the raised edge.

4. Three Point Touch: This technique is used to follow an elevated shoreline from below and to detect an objective above the shoreline. For example, this approach would be used to find the sidewalk while walking on the street. The three taps begin with a tap on the street side, followed by a tap against the curb and one last tap on top of the curb. The first tap and drag towards the curb is used to detect objects on the path, such as cars, and to maintain a straight path. The tap on top of the curb is used to determine if there is a sidewalk present (Terlau Rosanne, n.d.).

***Self Protection Technique:***

This technique is used when the person believes that there may be obstacles at head height. The free arm is raised and the forearm is placed diagonally across the face with the palm relaxed and facing outwards (refer to the appendix for illustrations on the navigation techniques with the long cane).

### 1.4.2 Navigation with Guide Dogs

The guide dog is used as an alternative navigation aid to the long cane. Prior to receiving a guide dog, however, the owner must complete a mobility training course with the long cane. Guide dogs are purpose bred and undergo a stringent selection process to ensure only the dogs with the most suitable personality become guide dogs. Dogs are trained to avoid all obstacles, including overhanging objects. As the dog and user navigate, the dog will guide the user around obstacles and if necessary, the dog will engage in intelligent disobedience and ignore the user's command in order to avoid a dangerous situation. For example, while preparing to cross the road, the dog will ignore the forward command and sit still if there is a car approaching.

The use of a guide dog is not suitable for all blind individuals. Guide dogs walk faster and thus require a greater level of confidence from the user. While the user communicates with the dog with vocal commands, the dog will communicate with the user exclusively through his movement. This means that the user must have a strong sense of balance to follow the dog's movement. Without the cane, the individual loses spatial feedback including surface material and, to a certain degree, his relative position to edges and walls. It is thus recommended that guide dog users undergo sensory training in order to boost their confidence as well as their spatial perception skills. Although dogs are trained to avoid overhanging objects, survey data indicates that users still run into objects above waist height while navigating with their guide dog. It is unlikely that the dog will always identify overhanging objects and safely navigate the user around them because the dog is primarily focused on objects at his height. Lastly, only about 1% of visually impaired individuals in the United States own a guide dog (Hersh, 2017).

## 1.5 Difficulties with Everyday Technologies

Blind individuals encounter challenges using devices for which sight is key to interacting with them. For example, a television remote control has no distinction between buttons aside from a small protrusions on the power, volume and channel buttons. The rest of the functions remain inaccessible.

Connecting a smartphone to a usb mini cable can be problematic because the port is both small and has a single orientation. For older individuals with lower dexterity this process may be more challenging and frustrating. Devices that require multiple steps and multiple menus for setup may be impossible to interact with unless they have been designed with accessibility in mind.

For a device to be accessible by the blind, the following must be true:

- Buttons and selections must be easily differentiable either through braille or some form of audio or haptic feedback
- Digital menus should include voice over
- Printed text must include braille transliteration

- Ports and plugs should be easy to identify and be reversible

However, it is important to note that this information is based on the extensive research and literature review done before interviewing blind individuals. Further information based on surveys will be reported later on in the report.

### 1.5.1 Flaws in Traditional Devices

***Long Cane:***
The main limitations of the cane include its association to disability and the extended training period required for effective use. Both act as large barriers even with the presence of government programs providing both canes and training for free. A discussion on the stigma associated to the use of assistive devices follows in the next section.

Since the optimal cane length is about four inches less than the user's height, the cane fails to provide the user with spatial information at a distance greater than the user's height. This may be dangerous given that the user will be completely unaware of dangerous situations further than the detection radius of the cane. Furthermore, none of the techniques allow for the user to detect obstacles both at ground and head height. In order to do so it is necessary for the user to combine a cane technique with the self protection technique. Doing so is both tiring and inconvenient as it occupies both hands.

Although cane techniques as well as different cane tips are designed to reduce the incidence of the cane getting stuck on cracks and uneven surfaces, these instances still occur. The cane is also unable to provide information about drop offs aside from their presence. Lastly the cane there is no way to detect objects moving at a speed towards the user.

***Guide Dog:***
Although they are trained to reduce the number of inconveniences they may present to the owner, they still present challenges like any other pet. Guide dog schools typically cover the entire cost of breeding, raising and training, but once ownership is transferred the financial burden is passed entirely to the owner. Guide dogs effectively navigate the user around spaces, however they don't always dodge overhanging obstacles meaning that users may sometimes injure their heads.

# 2 Project Strategy

## 2.1 Design Approach

### 2.1.1 Seven Principles of Universal Design

The Seven Principles of Universal Design were used to guide the design process of this device. These principles were developed in 1997 by the Center for Universal Design at the North Carolina State University College of Design in consortium with universal design researchers and practitioners from across the United States. The purpose of the principles is to guide the design of spaces and products towards greater usability and accessibility (Connell et al., 1997).

1. Equitable Use: The design is useful and marketable to people with diverse abilities
2. Flexibility in Use: The design accommodates a wide range of individual preferences and abilities
3. Simple and Intuitive Use: Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level
4. Perceptible Information: The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities
5. Low Tolerance for Error: The design minimizes hazards and the adverse consequences of accidental or unintended actions
6. Low Physical Effort: The design can be used efficiently and comfortably with minimum fatigue
7. Size and Space for Approach and Use: Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user;s body size, posture, or mobility

### 2.1.2 Iterative Design Process

The Iterative Design Approach is a commonly used cyclic conceptualization methodology that requires designer to rapidly generate prototypes, get feedback on those prototypes and make continued improvements to the design until a final product comes to shape (Wong & Park, 2017). This approach is most frequently used when the product in question has a significant user interaction component to it such as computer software (Poltrock & Grudin, 1996). The general trend that has been observed through the continued application of this method in industry is that the more design iterations there are the greater the usability of the device. This positive correlation is by no means linear. Rather, there are bursts of increase in product usability punctuated by periods of no change.

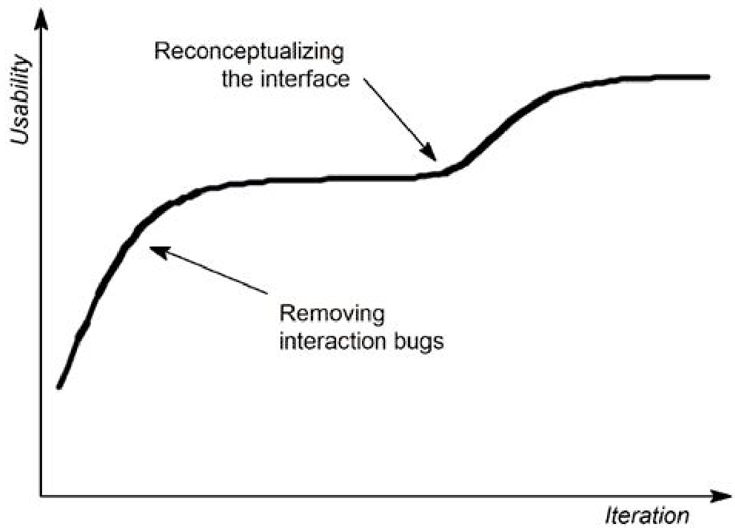


Figure 16: Visual demonstration of the relationship between number of iterations and the usability of the product

The practical limitations of this approach include a lack of access to users, speed of prototyping and a lack of communication between designers in charge of different aspects of the product resulting in prototype with unequally developed features (Poltrock & Grudin, 1996). These constraints can limit the success of this approach. However, acknowledging these flaws in the methodology and working to avoid them can make an iterative design approach very effective (Nielsen, 1993).

## 2.2 Introduction to BAT

### 2.2.1 Purpose

The Blindsight Assistive Technology (BAT) device is a battery-powered system that was designed to improve the quality and depth of spatial feedback provided to blind individuals to help them better navigate in indoor and outdoor settings. More specifically, the goal of this device was to reduce the incidence of injuries caused when blind individuals hit objects above the waist level. The BAT device was designed as a complimentary travel aid to the cane or the guide dog. As such, it was unable to provide safe mobility on its own and was thus categorized as a secondary aid.

### 2.2.2 High-Level Systems Perspective

From a systems level perspective, the BAT has a sensor module, a haptic feedback module, a power module and a processor module. The sensor module provides object proximity information through two ultrasonic sensors placed at either side of the users head. This information is converted into spatial feedback by the processor module that then correlates distance with a specific haptic feedback pattern. The haptic feedback module then relays the information to the user in a non-audio format through vibrational motors. The glasses module, in the implemented design of the two original designs we envisioned, had three power modules. One power module for the glasses and the other two for each of the separate bands.

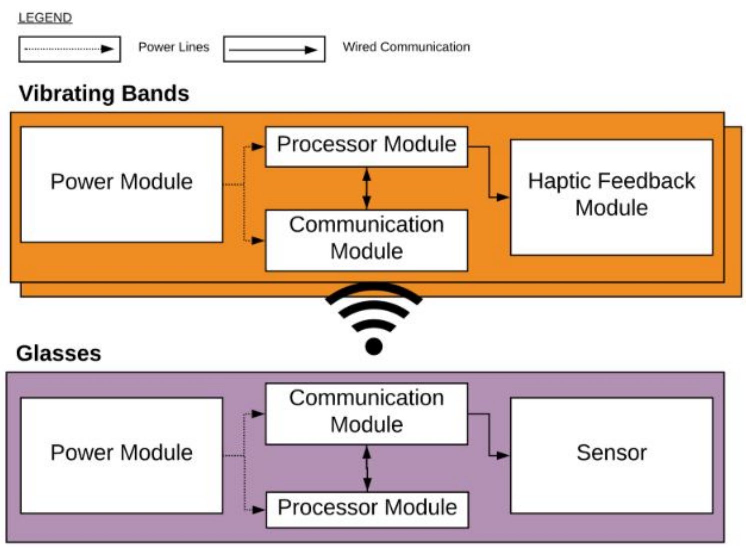


Figure 17: High-Level Block Diagram of the BAT

### 2.2.3 Design Constraints

***Size:***

To ensure comfort and mobility, the device electronics must be as small as possible in order to maintain device portability. The small form factor of the device indirectly places a constraint on the battery life since the physical size of the battery must be kept small. The size of the sensor is also limited which narrow the number of sensor technologies that can be used.

***User-Device Interaction:***

The device must seamlessly integrate into user's daily routines. This means the device must be made as intuitive as possible by reducing the number of steps that the user must take between purchasing the device and using it. In order to accomplish this goal, the device must provide clear feedback to the user in the form of simple and easily distinguishable vibration patterns for each scenario. Alerts regarding charging and battery status could also be added through auditive or vibrating feedback depending on the user's auditory level.

Studies have established a correlation between assistive device adaptability and device abandonment. Rates of abandonment are typically greater for devices that are unable to match the changing needs of the user and when unfriendly design makes it difficult for the user to adapt the device to his needs [6]. Changing needs are common with progressive conditions such as muscular degeneration and muscular dystrophy. Given the target audience, it is expected that the device must be able to easily adapt to changes in pace, reaction time and feedback intensity. Users may desire to receive warnings about obstacles at different distances over the time that they use the device and may require to adjust the intensity of the feedback for comfort. The user-friendly design of the device must take into account that the blind individual may encounter difficulties interacting with small, non differentiable buttons as well as typical charging ports, especially non reversible or non magnetic ports. These requirements guide the desire to implement buttons with particular shapes, such as a plus symbol to increase vibration intensity, as well as wireless charging.

It is important to consider factors beyond the sensor characteristics during the value analysis. One such factor is the time course of the average action potential in a neuron as it is a key determinant in the maximum resolution of the device. With a time course of 1mS, the maximum resolution that the user could perceive is 17cm. The calculation of the resolution follows:

$$v_{sound} \times Action\,Potential\,Time\,Course = Resolution \tag{1}$$

$$344m/s \times 1mS = 34.3cm \tag{2}$$

34.4cm is the distance that the sound wave could travel in the time that it takes the signal to reach the brain. Given that object detection is a two way trip, the device could detect an object that is 17cm away in that 1mS timeframe (Hoyle & Waters, 2010).

***Environment-Device Interaction:***

It is important to consider the ruggedness of the device given that it will be used outdoors in a variety of conditions. The ideal device would include an Ingress Protection Rating (IPX) greater than or equal to IPX-55. This means that the device would be protected from water splashes in any direction. It is important that the device is capable of resisting shock as the user may drop the device or bump it against an overhanging obstacle.

***Society-Device Interaction:***
According to Hersh, "the symbolic identification of the cane with blindness means that the cane may be seen as only for totally blind people, leading to some partially sighted people, newly blind people, and people with progressive conditions finding it difficult to accept or delaying cane use" (Pissaloux & Velázquez, 2017). Therefore, the device should be discrete, but it should (Alahakone & Senanayake, 2009) not follow the same approach as current medical devices that are meant to be hidden from view given their terrible aesthetic design (Pullin & Higginbotham, 2010). The device should ideally serve as a fashion item and the user should not feel the need to hide it. It should complement the looks of the user. This will help the user find the confidence to wear the device and beat the stigma. It is key that both the user and those around him find the device visually appealing. "Unsurprisingly blind people have been found to frequently share the general preference for small easily portable devices such as mobile and smartphones rather than larger more awkward and less easily portable devices" (Hersh, 2017).

***Maintenance:***
The team desires to make the device highly modular and relatively low cost in order to keep any maintenance and repair costs as low as possible. The motivation behind this approach is to reduce the burden of owning the device may place on the owner. Following a visit to the Abilities Conference in Boston, the team came to understand that there is little support in terms of insurance coverage for assistive devices. This often means that the high cost of assistive devices falls on the user. According to the National Census Bureau, visually impaired individuals have a median income that is half the median income of the United States. Furthermore, the vast majority of visually impaired individuals are covered under Medicaid and Medicare, neither of which cover non medically prescribed assistive technologies. This means that the users of the proposed device will most likely have to find alternate sources of funding to cover the device, and they are not guaranteed to find any. A short list, non comprehensive list of sources for assistive technology funding is available in the appendix.

The ultimate goal of the development of the device, regardless of its feasibility as a product around which a company may be built, is to provide a solution to improve the life of visually impaired individuals. Thus the development team wishes to open-source the design files for the device in hopes that the community of makers around assistive technologies will adopt the device and further its development well beyond what the current team is capable of achieving within the academic year timeframe.

### 2.2.4 Decision Matrix

Our general design approach was based on identifying specific categories that our customers would find important based on our product specifications and trying to satisfy these categories in our final product. The list of selected categories is given below:

- Performance: Battery life
- Affordability: Price per unit
- Reliability: Accuracy, Response time
- Ease of Use: Intuitive to use, Comfort
- Design: Durability, Acceptable aesthetic design, Modularity

Each component was given a specific sub-categories that was used to determine the overall main category ratings. In order to quantify the importance of the above qualities in each product, we developed a decision matrix. In this ranking technique, each cell's row category was compared to it's column category. The sum of each row was then scaled based on the importance of each factor. The total score of each component helped us prioritize the importance of different device characteristics in our final product.

Table 2: Decision Matrix for Rank Ordering of Design Goals

| | Performance | Affordabilty | Reliability | Ease of Use | Design | Total | Weight From Total | Total Chosen Weight Factor |
|---|---|---|---|---|---|---|---|---|
| **Performance** | | 1 | 0 | 0.5 | 0 | 1.5 | 37.5 | 40 |
| **Affordabilty** | 0 | | 0 | 0 | 0 | 0 | 0 | 25 |
| **Reliability** | 1 | 1 | | 1 | 1 | 4 | 100 | 100 |
| **Ease of Use** | 0.5 | 1 | 0 | | 0.5 | 2 | 50 | 50 |
| **Design** | 1 | 1 | 0 | 0.5 | | 2.5 | 62.5 | 65 |

### 2.2.5 Weight Assesment

The decision matrix above helped us prioritize our design considerations. A numerical value of "1" was given if the row category was deemed more important than the column category. Similarly, a numerical value of "0" was given if the opposite was considered true. A "0.5" was given for two design categories that were of equal importance and priority. Based on the results above, a weight from 1 to 5, 1 being of the least priority and 5 being of the highest priority, was given to each design condition. These assignments and their justification are given below.

1. Reliability: Device must accurately detect objects within its sensor's range with no false positives or false negatives.
    - Weight:100
    - The reliability of our BAT is a critical customer requirement due to the categorization of our device as a medical assistive technology. Even though the device will not be FDA approved and therefore will not have to adhere by official medical device stipulations, the potential liability associated with a poor accuracy sensing is very high. Furthermore, a main selling point for BAT is its low cost without a compromise in quality of detection. For these reasons, this design condition was given the highest weight factor.
2. Design: Device must be physically appealing, pass Ingress Protection Marking-55 (IP-55) durability testing, and have a modular design.
    - Weight: 65
    - A common theme witnessed with assistive technologies is their lack of penetration and use in the the target market. Reasons for this have been pinpointed to social stigmas against devices as well as the inconvenience of using a device in certain situations. For this reason, making our device look physically appealing is considered of utmost importance in ensuring the use of our device by blind individuals. Durability and modularity are also important customer requirements to make BAT more convenient to use. For these reasons, this design condition was given the second highest weight factor.
3. Ease of Use: Device must be intuitive to operate and comfortable to wear.
    - Weight: 50

- The target market for BAT is all blind individuals which includes a broad range of technological literacy. For this reason, our device must be developed such that its operation is as intuitive as possible. This can be achieved by mimicking the front-end design of common devices such as home appliances. Since the device is intended for prolonged use, comfort is also prioritized as an important customer requirement. For these reasons, this design condition was given the middle weight factor.

4. Performance: Device must be able to operate on only the battery for a minimum of 10 hours, 2 hours continuously with intermittent use for the other 8 hours.
   - Weight: 40
   - Regardless of the fulfillment of the other customer requirements and any added benefit the device gives to the user, if the BAT cannot last for the expected operation period than the device becomes ineffective. Therefore, to ensure that blind individuals are able to rely on the device to enhance their quality of life the assistive technology must be backed up with a powerful battery. The implementation of this design condition is fairly simple, therefore this consideration was given the second lowest weight factor.

5. Affordability: Device cost per unit must be less than $75.
   - Weight: 25
   - A low cost for our device would allows the BAT to target a larger market space. However, if the cost exceeds the stated threshold this would simply narrow our market. For this reason, seeing as this customer requirement is not of critical importance it was given the lowest weight factor.

## 2.3 Specific Module Design Options

In the previous section, the general design categories were identified and ranked. This prioritization was useful in the overall product development process. However, when choosing specific components used in our device the categories were made more specific. When choosing the components, multiple models and brands were compared based on technical specifications. The final decision was made keeping the broad customer requirement themes in mind.

During the value analysis, each component was given different subcategories that helped determine the overall top category. The overall top category was assigned as the rating average of all subcategories. This approach gave us a better understanding of the specific features that each component was capable of delivering, and how it was valued for our application.

### 2.3.1 Sensor

Table 3: Value Analysis for Sensor

| *Considerations* | *Sensor* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Ultrasonic Two-Can HC-SR04** | | | **Ultrasonic One-Can MB-1040** | | | **Time of Flight (TOF) VL53L0X** | | |
| | Value | Weight | Score | Value | Weight | Score | Value | Weight | Score |
| **Reliability (100)** | | 6 | 600 | | 6 | 600 | | 7 | 500 |
| Resolution | 0.3cm | 6 | | 2.5cm for >15cm | 8 | | | | |
| Sampling Frequency | 40Hz | 6 | | 20Hz | 4 | | 33Hz | 5 | |
| Range | 0.02 - 4m | 6 | | ~6.5m | 8 | | 2m | 4 | |
| Field of View | 15deg | 5 | | 55deg (rect.) | 4 | | 25deg | 6 | |
| **Design (65)** | | 3 | 195 | | 6 | 390 | | 10 | 650 |
| Size (LxWxT) | 45x20x15mm | 3 | | 19.9x22.1x15.5mm | 6 | | 4.4x2.4x1mm | 10 | |
| **Ease of Use (50)** | | N/A | | | N/A | | | N/A | |
| **Performance (40)** | | 6 | 240 | | 10 | 400 | | 7 | 280 |
| Active Current Consumption | 15mA | 3 | | 2mA | 10 | | 19mA | 2 | |
| Quiescent Current Consumption | <2mA | 4 | | | | | 5-6uA | 10 | |
| Operating Voltage | 5V | 10 | | 2.5-5.5V | 10 | | 2.6-3.5V | 10 | |
| **Affordability (25)** | $3.95 / sensor | 8 | 200 | $30.18 / sensor | 3 | 75 | $13.29 / sensor | 5 | 125 |
| **TOTAL** | | | 1235 | | | 1465 | | | 1555 |
| *Weights* | *10=Excellent, 8=Good, 6=Satisfactory, 4=Mediocre, 2=Unacceptable, 0=Failure* | | | | | | | | |

- Ultrasonic Two-Can HC-SR04
  - Reliability: The range and field of view (FOV) is at an average level. The sampling frequency and resolution are also at a mid-level compared to the other sensors.
  - Design: This sensor scores very poorly in the design category due to its large size. The two-can design is bulky and if used would probably not be physically appealing.
  - Performance: The active and quiescent current consumption is very high which will reduce battery life significantly.
  - Affordability: The cost per unit is the lowest of the three sensors and decreases as more units are purchased.

- Ultrasonic One-Can MB1040
  - Reliability: The range and field of view (FOV) for this sensor is very good. In contrast, the sampling frequency and resolution are at a mid-level compared to the other sensors.
  - Design: This sensor scores better than the previous sensor because only one-can is used to both transmit and receive which makes the design less bulky.
  - Performance: The active and quiescent current consumption is very low which greatly improves battery life.
  - Affordability: The cost per unit is very high but goes down as more units are purchased.
- Time of Flight VL53L0X
  - Reliability: The range and field of view (FOV) for this sensor is at an average level. The sampling frequency is very high which implies that the sensor has a very high resolution.
  - Design: The sensor is made using a very small Single Photon Avalanche Diodes which gives it a desirable compact form factor.
  - Performance: The active current is very high for this sensor but is compensated by the very low quiescent current consumption.
  - Affordability: The cost per unit at a mid-range level but goes down as more units are purchased.

### 2.3.2 Haptic Feedback Actuator

Table 4: Value Analysis for Haptic Feedback Actuator

| *Considerations* | *Haptic Feedback Actuator* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Precision Vibration Motor 310-101** | | | **Seeed Tech Vibration Motor 31604004** | | | **Micro Servo SG90C** | | |
| | Value | Weight | Score | Value | Weight | Score | Value | Weight | Score |
| **Reliability (100)** | | 7 | 700 | | 7 | 700 | | 8 | 800 |
| Vibration Amplitude | 0.8G | 7 | | 0.8G | 7 | | 1.2kg/cm | 7 | |
| Rate Speed | 200Hz | 6 | | 167Hz | 6 | | 500Hz | 8 | |
| **Design (65)** | | 8 | 520 | | 9 | 585 | | 6 | 390 |
| Frame Diameter | 10mm | 8 | | 10mm | 8 | | 22.6x12.2x30mm | 7 | |
| Body Length | 3.4mm | 8 | | 2.7mm | 9 | | | | |
| Weight | 1.2g | 9 | | 0.9g | 10 | | 9g | 7 | |
| **Ease of Use (50)** | | N/A | | | N/A | | | N/A | |
| **Performance (40)** | | 6 | 240 | | 6 | 240 | | 6 | 240 |
| Rated Current | 75mA | 2 | | 80mA | 2 | | High | 2 | |
| Voltage | 2.5-3.8V | 10 | | 2.5-3.5V | 10 | | 3.5-6V | 10 | |
| **Affordability (25)** | $1.95/unit | 8 | 200 | $1.20 / sensor | 9 | 225 | $4 / sensor | 6 | 150 |
| **TOTAL** | | | 1660 | | | 1750 | | | 1645 |
| *Weights* | *10=Excellent, 8=Good, 6=Satisfactory, 4=Mediocre, 2=Unacceptable, 0=Failure* | | | | | | | | |

- Precision Vibration Motor 310-101
  - Reliability: The vibration amplitude is at an acceptable level such that the user can recognize any received feedback. The maximum frequency of vibrations is fairly low which may increase the response time afforded to the whole device.
  - Design: The small diameter and low weight of the motor makes it ideal for the BAT application where concealment of the sensor and comfort are critical customer requirements.
  - Performance: The high current consumption is highly undesirable due to the battery-powered nature of the device.
  - Affordability: The sensor is relatively inexpensive and the price goes down as more units are purchased.
- Seeed Tech Vibration Motor 31604004
  - Reliability: The vibration amplitude is at an acceptable level such that the user can recognize any received feedback. The maximum frequency of vibrations is even lower than the previous motor which only increases device response time.

- Design: The small diameter and low weight of the motor makes it ideal for the BAT application. The weight is lower than the previous sensor which makes the device more comfortable to wear.
- Performance: The high current consumption is again highly undesirable due to the battery-powered nature of the device.
- Affordability: The sensor is inexpensive and the price goes down as more units are purchased.

- Micro Servo SG90C
  - Reliability: The vibration amplitude is at an acceptable level such that the user can recognize any received feedback. The maximum frequency is at a high enough level that it response is faster than the fastest reaction time the device will encounter while attempting to avoid objects.
  - Design: Compared to the vibrating motors, the device is more bulky and harder to conceal. However, it is still small enough that a haptic feedback design can look discrete.
  - Performance: The current consumption is not given, however based on the nature of motors it is likely that a significant current draw will be seen ($>$ 100mA).
  - Affordability: The sensor is relatively expensive but the price goes down as more units are purchased.

## 2.4 Microcontroller

Table 5: Value Analysis for Microcontroller

| *Considerations* | *Microcontroller* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Arduino Pro Mini** | | | **NodeMCU** | | | **MSP430 Ultra Low-Power** | | |
| | Value | Weight | Score | Value | Weight | Score | Value | Weight | Score |
| **Reliability (100)** | | 7 | 700 | | 6 | 600 | | 8 | 800 |
| **Design (65)** | | N/A | | | N/A | | | N/A | |
| **Ease of Use (50)** | | N/A | | | N/A | | | N/A | |
| **Performance (40)** | | 9 | 360 | | 5 | 200 | | 10 | 400 |
| Operating Voltage | 3.3V | 9 | | 3.3V | 9 | | 1.8-3.6V | 10 | |
| Active Current | 4.74mA | 9 | | 80mA | 1 | | 290uA | 10 | |
| Quiescent Current | 0.9mA | 10 | | 12mA | 2 | | 1.1uA | 10 | |
| Digital IOs | $14 | 10 | | 11 | 8 | | 53 | 10 | |
| **Affordability (25)** | $2.94/unit | 8 | 200 | $2.98/unit | 8 | 200 | $3.74/unit | 6 | 150 |
| **TOTAL** | | | 1260 | | | 1000 | | | 1350 |
| *Weights* | *10=Excellent, 8=Good, 6=Satisfactory, 4=Mediocre, 2=Unacceptable, 0=Failure* | | | | | | | | |

- Arduino Pro Mini
  - Reliability: The score for this design category is estimated based on the expected failure that might occur in different circuits due to manufacturing discrepancies between different units. To quantify this, the number of false positives that might arise due to the speed of information processing is considered.
  - Performance: The active and quiescent current consumption is very low which is highly desirable to prolong battery life.
  - Affordability: The sensor is relatively inexpensive and the price goes down as more units are purchased.
- NodeMCU
  - Reliability: Again, the score for this design category is estimated based on the number of false positives expected. The NodeMCU is manufactured by a less established company compared to the other two microcontrollers, therefore the quality of manufacturing was predicted to be lower explaining the lowered score.
  - Performance: The active and quiescent current consumption is very high which would significantly reduce battery life.

  - Affordability: The sensor is relatively inexpensive and the price goes down as more units are purchased. However, the reduced price does not compensate adequately for the inferior characteristics that the MCU has in comparison to its competitors.

- MSP430 Ultra Low-Power
  - Reliability: The MSP430 is a very reliable chip that has been tried and tested for many years in numerous applications. Furthermore, Texas Instruments is an established company therefore number of false positives expected is very low.
  - Performance: The active and quiescent current consumption is very low which is great for the device battery life.
  - Affordability: The sensor is slightly more expensive than its competitors but the price is justified by the low power consumption and reliability of the device.

## 2.5 Battery

Table 6: Value Analysis for Battery

| *Considerations* | *Battery* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **NiMh HHR-70AAAE4** | | | **LiPo DTP301120** | | | **Supercapacitor BZ055B203ZSB** | | |
| | Value | Weight | Score | Value | Weight | Score | Value | Weight | Score |
| **Reliability (100)** | | 7 | 700 | | 7 | 700 | | 5 | 500 |
| **Design (65)** | | N/A | | | N/A | | | N/A | |
| Size (LxWxT) | 48.3x14.5x14.5mm | 5 | | 3.5x11.5x22mm | 10 | | 20x15x2.3mm | 3 | |
| **Ease of Use (50)** | | N/A | | | N/A | | | N/A | |
| **Performance (40)** | | 7 | 280 | | 7 | 280 | | 5 | 200 |
| Average Discharge Capacity | 780mAh | 10 | | 40mAh | 6 | | N/A | 0 | |
| Length at Which Internal Resistance Becomes Significant | 35m | 5 | | <250m | 9 | | 100m | 7 | |
| Nominal Voltage | 1.2V | 6 | | 3.7V | 7 | | 3.6V | 7 | |
| Charging Voltage | 1.6V | 8 | | 4.2V | 3 | | <3.6V | 8 | |
| **Affordability (25)** | $1.72/unit | 9 | 225 | $0.5-1.8/unit | 10 | 250 | $12.51/unit | 2 | 50 |
| **TOTAL** | | | 1205 | | | 1230 | | | 750 |
| *Weights* | *10=Excellent, 8=Good, 6=Satisfactory, 4=Mediocre, 2=Unacceptable, 0=Failure* | | | | | | | | |

- NiMh HHR-70AAAE4
  - Reliability: For batteries, the reliability is directly linked to the performance because the battery life decides how much the developed can depend on the device to last. In terms of manufacturing discrepancies, all three batteries are assumed to have an equal quality of manufacturing therefore the reliability is not affected by individual battery characteristics.
  - Design: This battery comes in a cylindrical double AA form factor is therefore fairly bulky and difficult to conceal.
  - Performance: The average discharge capacity is very high, however, the nominal voltage is low relative to the average microcontroller operating voltage. This means that for this battery multiple units would have to be put in series.
  - Affordability: The low cost of the battery and its prevalence in most department stores are both very attractive product features.
- LiPo 301120
  - Reliability: Look at previous battery description.

  - Design: This battery comes in a flat disc form factor which is easy to conceal and allows greater variability in overall device form.
  - Performance: The average discharge capacity is at the mid-range level high, however, the nominal voltage exceeds the average microcontroller operating voltage.
  - Affordability: The low cost of the battery and ubiquitousness of the battery are both desirable features.

- Supercapacitor BZ055B203ZSB
  - Reliability: Look at previous battery description.
  - Design: This battery comes in a bulky package that is hard to conceal.
  - Performance: The nominal voltage exceeds the average microcontroller operating voltage.
  - Affordability: The high cost of the component and the lack of prevalence in ordinary consumer stores makes this option very unattractive.

## 2.6 Power Management Integrated Circuit

Table 7: Value Analysis for Power Management IC

| *Considerations* | *Power Management IC* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **LTC3106** | | | **STC3117** | | | **MCP73831** | | |
| | Value | Weight | Score | Value | Weight | Score | Value | Weight | Score |
| **Reliability (100)** | | 9 | 900 | | 8 | 800 | | 9 | 900 |
| **Design (65)** | | 10 | 650 | | 10 | 650 | | 10 | 650 |
| Support for LiPo | Yes | 10 | | Yes | 10 | | Yes | 10 | |
| **Ease of Use (50)** | | N/A | | | N/A | | | N/A | |
| **Performance (40)** | | 7 | 280 | | 9 | 360 | | 9 | 360 |
| Quiescent Current | 1.6uA | 8 | | 2uA | 7 | | 0.1uA | 10 | |
| Active Current | | 5 | | 40uA | 10 | | 510uA | 7 | |
| **Affordability (25)** | $6.79/unit | 3 | 75 | $1.56/unit | 8 | 200 | $0.43/unit | 10 | 250 |
| **TOTAL** | | | 1905 | | | 2010 | | | 2160 |
| *Weights* | *10=Excellent, 8=Good, 6=Satisfactory, 4=Mediocre, 2=Unacceptable, 0=Failure* | | | | | | | | |

- LTC3106
  - Reliability: This component is produced by Linear Technologies, an established company with a very good reputation in industry, therefore the number of defect between individual products due to manufacturing discrepancies is expected to be low.
  - Design: Support for a Lithium Polymer battery is critical when choosing this IC because that is the battery that is likely to be used based on the previous value analysis.
  - Performance: The quiescent current consumption is low which is a desirable feature for this component.
  - Affordability: This component is relatively expensive, but the price goes down as more units are purchased.
- STC3117
  - Reliability: This component is produced by ST Microelectronics therefore the reliability of the device is very high since manufacturing discrepancies between individual units can be expected to be low.
  - Design: This device supports both Li-Ion and Li-Po battery charging.

  - Performance: The quiescent current consumption is fairly low. The active current consumption is really good in comparison to the competing products.
  - Affordability: This component is very inexpensive compared to other products and the cost only goes down as more units are purchased.

- BQ24079
  - Reliability: This component is produced by MicroChip therefore the manufacturing tolerances are very high and adherence to the standard is expected to be very good.
  - Design: This device supports both Li-Ion and Li-Po battery charging.
  - Performance: The quiescent current consumption is very low which is attractive for wearable devices because of the boost it will provided in terms of battery life.
  - Affordability: This component is comparatively very cheap and the price goes down as more units are purchased.

## 2.7 Gantt Chart

Following the iterative design methodology, the timeline that was adopted followed a cyclic prototyping approach. First, the sensors were tested in an initial rough prototype. Following this, each module was tested separately with standalone circuitry. Inputs from other modules necessary for the testing of the module in question were simulated using software. After verifying the functionality of all the modules on their own, each of the standalone circuits were individually integrated into a larger board. This system integration phase generated multiple prototypes as the circuit was tested after the addition of each significant module.

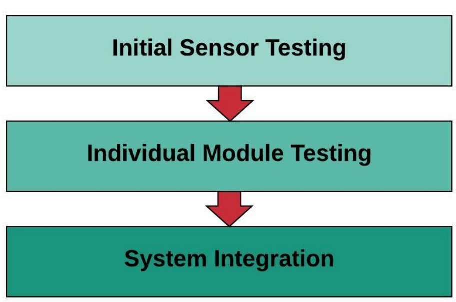


Figure 18: Visual demonstrating the specific approach followed in the design of the BAT in chronological order

A gantt chart was made at the very beginning of the project to outline a structured plan to achieve our project goal. This chart was repeatedly updated throughout the year to reflect changes in our project. The final iteration of this chart is shown below.

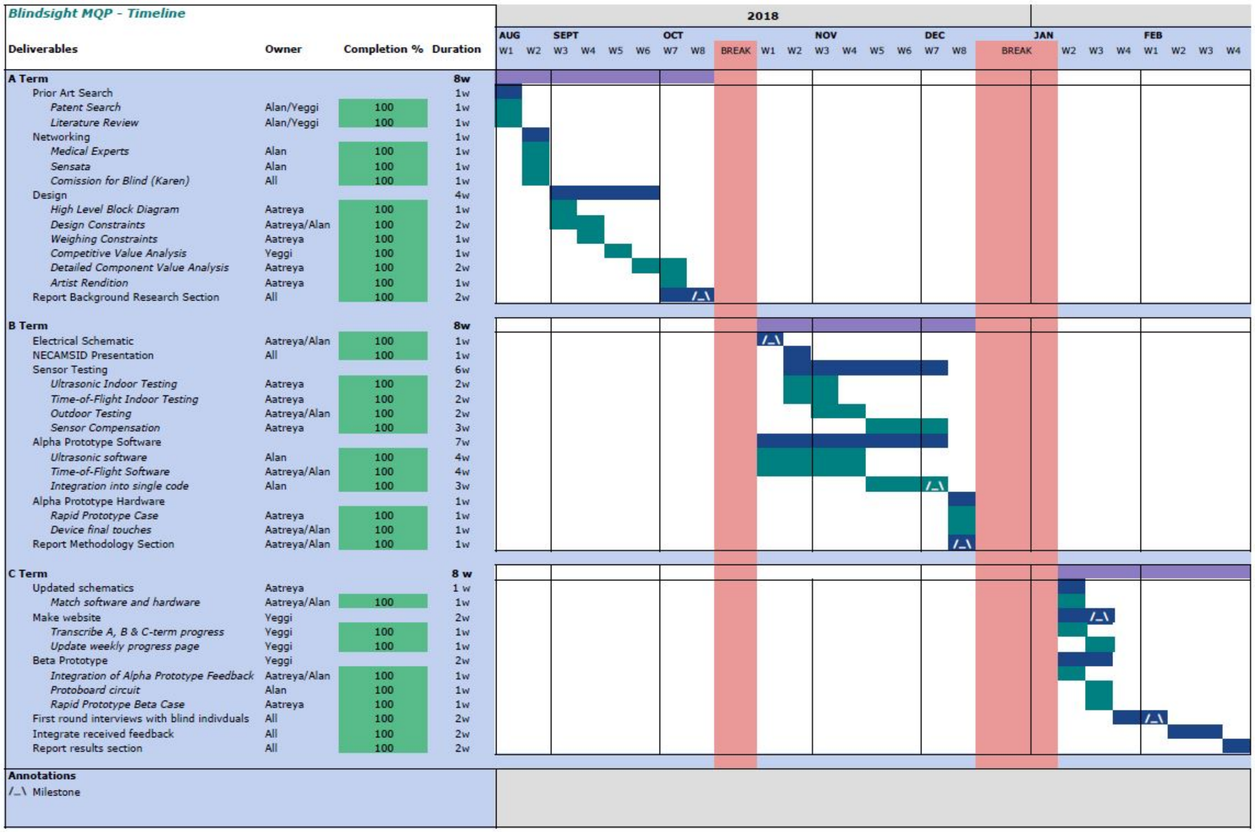


Figure 19: Gantt Chart representing the timeline of our project

# 3 Product Development

In this section, the application of the iterative design methodology in our project is explored in detail. The testing and integration of each module and feature is discussed in chronological order.

## 3.1 Sensor Module Integration

### 3.1.1 Sensor Testing

Initially, two sensors were considered for our device: the VL53L0X Infrared Ranging Sensor and the MB1020 Ultrasonic Sensor. To determine which component would be best for our application, the sensors were tested in different environments. The same test was carried out for both components. The sensor circuit was mounted to a movable cart and a cardboard sheet was placed in front of it. The distance from the sheet to the sensor was increased in consistent increments until the distance readings were maxed out. This test was carried out in an indoor and outdoor setting. The indoor setting was a tight corridor and the outdoor setting was a open driveway. These settings best simulate the environments that our device would encounter.


Figure 20: Testing MB1020 Ultrasonic sensors outdoors in an open driveway

A secondary objective of sensor testing was to verify if the sensor data given in each component's datasheet was accurate. Therefore, the results for each sensor were compared to the typical performance specifications found in their respective datasheets.

***VL53L0X Testing:***

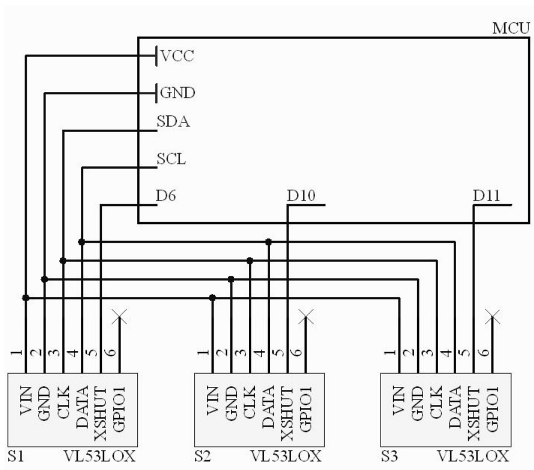


Figure 21: Standalone circuit used to test the VL53L0X Infrared Sensor

The circuit shown in figure 21 was used to test the functionality of the VL53L0X Infrared sensor. In the circuit, there are four common lines coming from the microcontroller: power, ground, shared clock line (SCL) and shared data line (SDA). The SDA and SCL lines belong to the I2C bus that is used to collect the proximity data generated by each sensor. Each sensor has a unique XSHUT line connected to individual digital pins on the microcontroller. Since the data lines are shared among sensors, the XSHUT pin is used to ensure that no two sensors are sending data at the same time.

According to the sensor datasheet, when the sensor is in default mode the proximity data should follow a fairly linear calibration graph very close to the line of identity (ST Microelectronics, 2018).

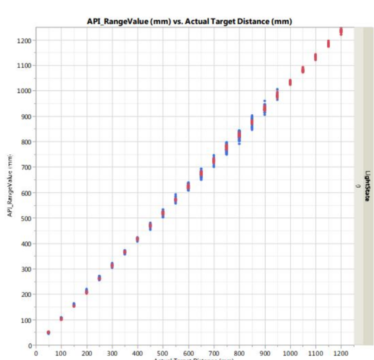


Figure 22: Expected calibration graph given in the VL53L0X datasheet

After performing our own testing (for which the raw data can be found in Appendix A), a similar linear trend was observed with an average sensitivity of 1.0007 mm/mm. This is very close to the ideal sensitivity of 1 mm/mm described in the sensor datasheet. An average DC offset of -36.1 mm was also recorded. Due to the low resolution that is needed for our application, this offset was not considered significant. The maximum distance the VL53L0X sensors were able to detect was around 1.75 m.

***MB1020 Testing:***

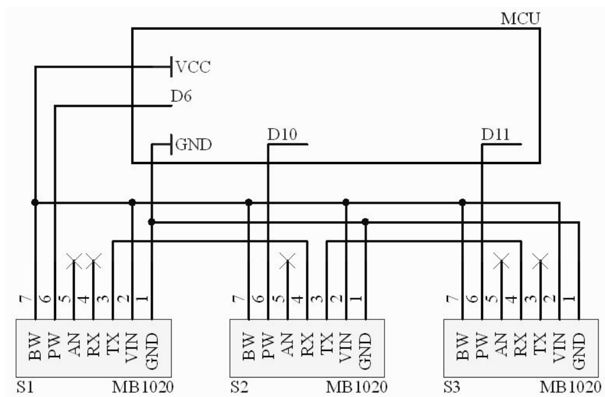


Figure 23: Standalone circuit used to test the MB1020 Ultrasonic Sensor

The circuit shown in figure 23 was used to test the functionality of the MB1020 Ultrasonic sensor. The two common lines in this circuit are the power and the ground. Each component's receiver (RX) pin is connected to the previous component's transmitter (TX) pin. The reason for this setup is due to the way the sensors are configured. According to the datasheet, in order to avoid multiple sensors pinging at the same time the first sensor produces a signal that triggers the next sensor on the chain. This signal is generated once the sensor has finished collecting data or after 50ms have elapsed. This process then continues until the last sensor is reached. The unique connection on each component, the pulse width (PW) pin, communicates the proximity information to a digital pin. The length of the pulse width directly correlates with the proximity value that is being reported.

There are two other recommended configurations in the manufacturer-provided datasheet that could have been used. The first one, a "PW Output Constantly Looping" configuration, is a slight modification on the "PW Output Commanded Loop" configuration that was used in our final circuit. The modification is the feeding back of the TX pin to the RX pin of the first sensor resulting in a circuit that requires only a single trigger to start a cyclic sensor collecting cycle. The other alternative configuration is the "PW Output Simultaneous

Operation" which has all the sensor RX pins connected together. This means that all the sensors are on at the same time and are collecting proximity information simultaneously. The drawback of this approach is the higher likelihood of interference from adjacent sensors which is why this configuration was not used.

For sensor testing, MatBotix provided calibration beam patterns in the sensor datasheet, however the calibration curves used to acquire those beam patterns were not provided. Therefore, the MB1020 sensor characterization was based on the testing that was conducted for this project (raw data can be found in Appendix A). From the analysis of the results, it was concluded that there was an in-built sensitivity multiplication factor of approximately x5. For the sake of convenience while testing and for demonstrating to the project's evaluators, this factor was removed by subtracting the average DC offset and dividing by the average sensitivity. However, for the final product the sensitivity factor was left in because the increased sensitivity would be beneficial to users. The maximum distance before the sensor was unable to collect proximity information was greater than 6 m.

***Elimination of ToF Sensor:***

After completing all the testing, a decision was made to go with the MB1020 Ultrasonic sensor. The main factor behind this decision was the increased proximity sensing sensitivity and lower susceptibility to interference from the environment. The VL53L0X Infrared sensor, on the other hand was very susceptible to light and had a much lower maximum measuring distance. Furthermore, it had a much lower sampling rate which was a major impediment to its usage in any real-time application including in the BAT.

***Sensor Delay Debugging:***

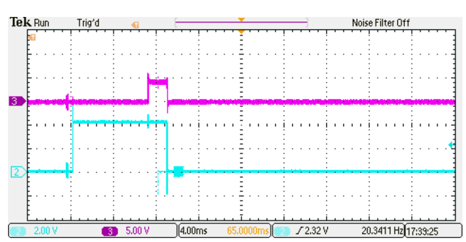


Figure 24: Sensor Distance Readings Overlapping

Following the analysis of the trigger signals with the oscilloscope it was discovered that the timing of the signals was not as expected. For the device to operate as intended, $Sensor_1$ (purple) should trigger first followed by $Sensor_2$ (cyan). As seen in figure 24, however, the trigger signal for $Sensor_2$ was taking place before that of $Sensor_1$. This was indicative of a major issue with either the software or the hardware as $Sensor_1$ produces the trigger signal that activates $Sensor_2$. The waveform suggested that $Sensor_2$ was ranging regardless of the trigger signal produced by $Sensor_1$. As a result of this unexpected behavior, $Sensor_1$ was producing smaller measurements than expected even though both sensors were placed at the same distance from the the same obstacle. When $Sensor_2$ was obstructed, the resulting pulse decreased, as expected, and $Sensor_1$ reported the expected distance to the obstacle. Since no inconsistencies were found between the suggested wiring of the sensors in the datasheet and the prototype, it was concluded that there must have been a problem with the hardware itself. More specifically, that the circuitry to produce the TX signal at $Sensor_1$ was not working properly. The sensors were then connected directly to the MCU to be triggered individually. The new configuration resulted in the correct, expected waveform from both sensors. This configuration introduces a small, negligible delay since the MCU triggers the next sensor when it recognizes the end of the distance measurement instead of the arrival of the ultrasonic pulse to the sensor. The alternative configuration, where one sensor triggers the next, does not suffer from this delay because the next sensor is triggered immediately upon the arrival of the ultrasonic pulse.

## 3.2 Motor Module Integration

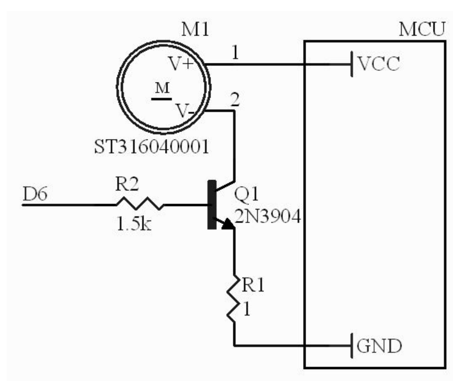


Figure 25: Standalone circuit used to test the ST Vibrating motor

The circuit shown in figure 25 was used to test the operation of the ST Vibrating motor. In the circuit, a BJT with an emitter and a base resistor is used. The base resistance reduces current sourcing from the base and the emitter resistor is used to limit current flow through the motor.

Initially when testing the motor, the current characteristics that were observed were abnormal. Rather than seeing a clean square wave as expected, some major transient effects were present.

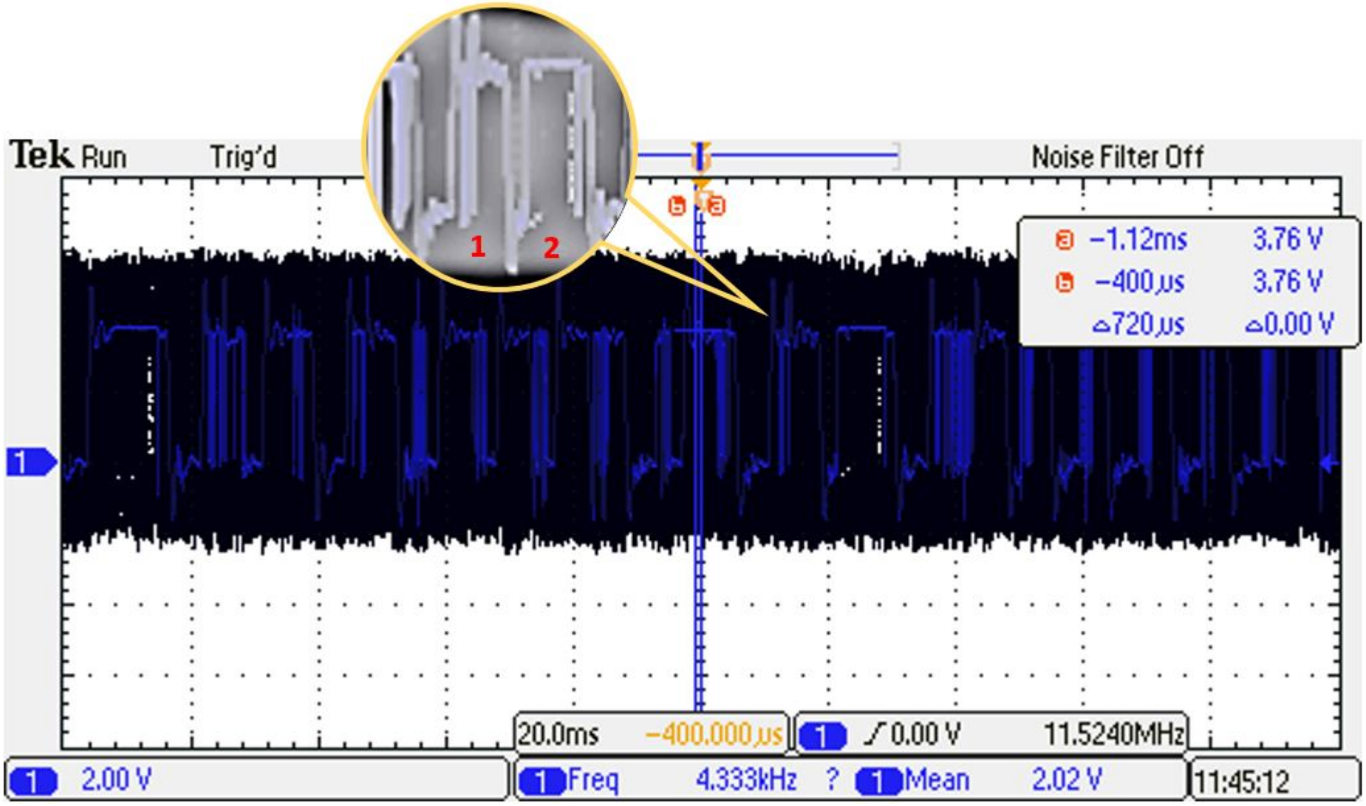


Figure 26: Motor current characteristics acquired by measuring the potential across the 1ohm base resistor

In the blown-up view in Figure 26, two consecutive signal periods are shown. In the second waveform period, a relatively clean square wave is visible. In contrast, the first period exhibits a large transient in the high band. After some testing, we determined that the reason for this was the frequency of pulse-width modulated (PWM) signal generated by the Arduino was matching the frequency of the mechanical movement of the vibrating motor. The conclusion that was reached was that the off centering of the internal weight in the shaft of the motor was occurring at the same time as the transition of the PWM signal from high to low resulting in second-order transients in the early part of the high band. By simply changing the Arduino PWM signal property from "default PWM" (977Hz) to "Fast PWM mode" (16MHz), the motor current waveform became significantly cleaner.

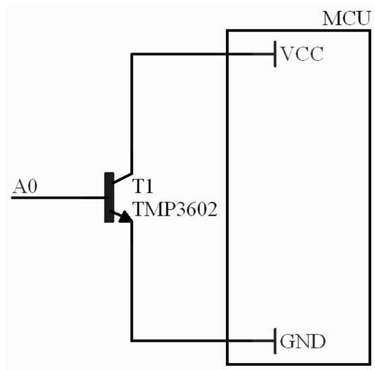


Figure 27: Standalone circuit used to test the TMP3602 Temperature sensor

## 3.3 Temperature Sensor Integration

According to the MB1020 Ultrasonic sensor datasheet, the in-built recalibration at the start of each ranging cycle is designed to compensate for changes in the sensor ringdown pattern due to changes in temperature. "If the temperature, humidity, or applied voltage changes during operation, the sensor may require recalibration to reacquire the ringdown pattern" (MaxBotix, 2015). Based on this information, a decision was made to add a simple resistive temperature sensor and to force the device to recalibrate every time a 5°C change in the environment was detected. The circuit shown in figure 27 was used to test the functionality of the TMP3602 Resistive Temperature sensor. The temperature was artificially changed by exposing the temperature sensor to warm air. A thermometer was used to determine when the temperature had increased by 5°C and the serial monitor was used to determine if a recalibration sequence had been initiated.

## 3.4 Communication Module Integration

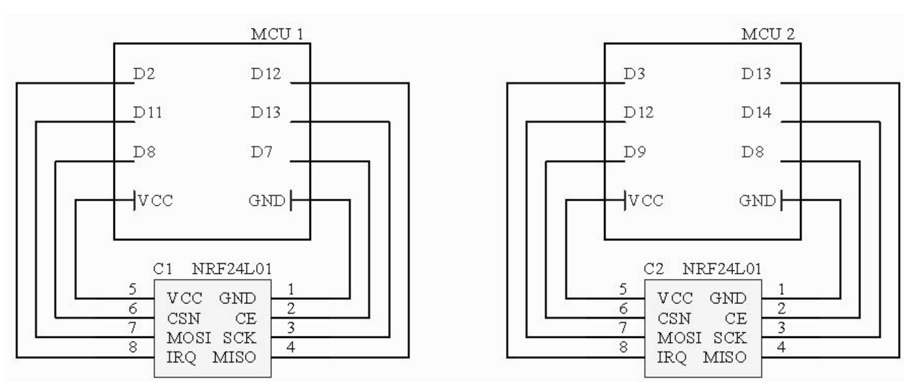


Figure 28: Standalone circuit used to test the NRF24L01 Wireless transceiver

The circuit in Figure 28 was used to test the communication range and general functionality of the NRF24L01 Wireless transceiver. In the circuit, there are two transceivers, each connected to a different microcontroller. The NRF chip is controlled through the SPI ports Master-In-Slave-Out (MISO) and Master-Out-Slave-In (MOSI). Subsequently, a Shared Clock (SCK) pin is necessary between the Master and Slave to synchronize communication and a SPI Enable (CSN) pin is necessary to turn serial communication on and off. Finally, the Chip Enable (CE) pin is used to turn on and off communication between chips and the Interrupt Routine (IRQ) pin is used to trigger a hardware interrupt.

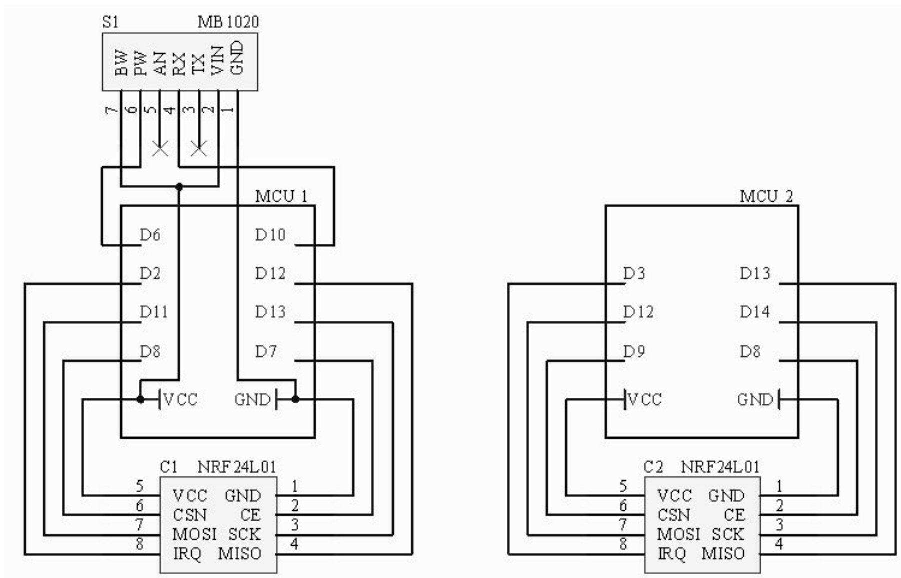


Figure 29: Standalone circuit used to test the NRF24L01 Wireless transceiver along with a single sensor

The circuit in Figure 29 was used to measure the delay of the combined communication and sensor modules to isolate the components contributing to a high overall system delay. In this circuit, there are two transceivers. One transceiver is connected to a single ultrasonic sensor. The data that is received from the sensor is sent to the next transmitter. This process is carried out repeatedly. The main purpose of this circuit was to identify delays in our system. However, during this process a more significant problem was uncovered. When hooking up the trigger pin, the pin used to initiate ranging in the sensor, to an oscilloscope along with sensor pulse width pin, the output trigger pin output was expected to be a 20$\mu$S square pulse. However, what was observed was a sharp transition followed by an extended decaying period as shown in Figure 30. Connecting a 1k$\Omega$ resistor from the trigger pin to ground resulted in a 60Hz power line noise wave to be displaying on the oscilloscope. This suggested that the PWM output node from the Arduino had a very high impedance. Subsequently, placing a small resistance in parallel with a high resistance resulted in the lower resistance voltage appearing "stronger" than the actual PWM signal.

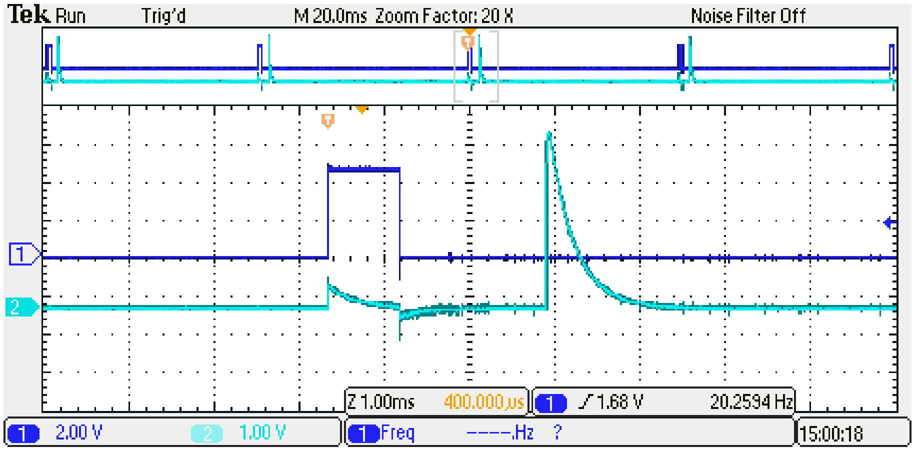


Figure 30: Oscilloscope image of original waveform

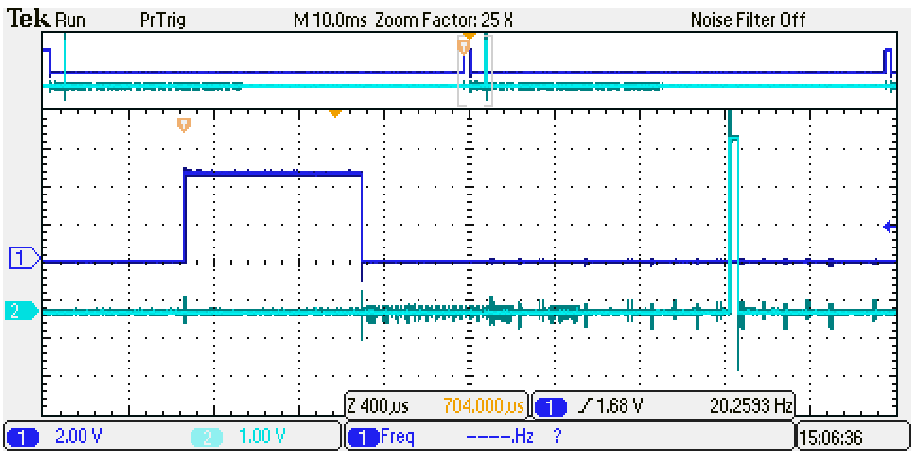


Figure 31: Oscilloscope image of waveform after correcting the code

Looking into the code, it was discovered that since we had not assigned the PWM pin to any specific function (Input or Output) it had defaulted to an input configuration which has a high impedance. The impedance was decreased by simply assigning the PWM pin as an output. The resulting waveform (shown in Figure 31) had a trigger pin output that more closely resembled a square wave. The lesson learnt here was transferred to our system code where we found other pins that were not assigned as either inputs or outputs.

## 3.5 Evolution of Device Casing

The casing for the BAT went through multiple iterations as the size of the circuit board that was used became smaller and components were added in different arrangements on the board. In total, three major casing iterations were made before the final casing was decided on.

***First Iteration Casing:***

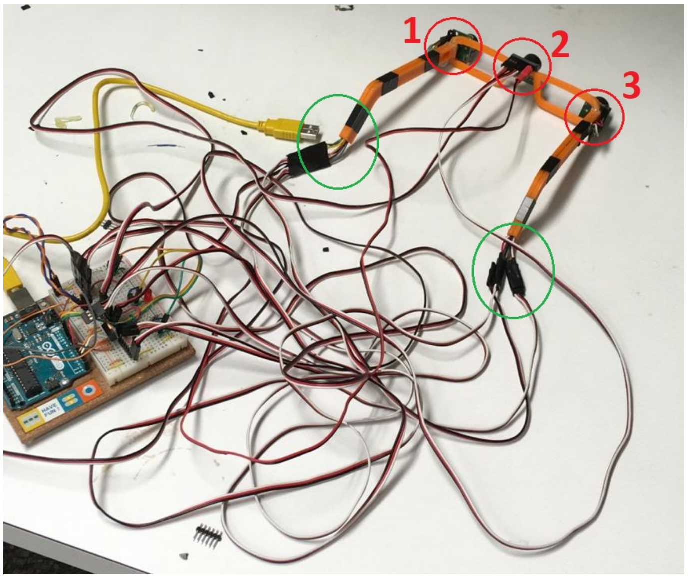


Figure 32: Top view of first iteration of casing

The first iteration, shown in Figure 32, three sensors were placed at the right, left and center of the frame (circled in red). When this casing was made, the communication module had not been integrated into our system and the majority of the circuitry excluding the sensors were still on a breadboard. Therefore, the casing was made with hollow frames to allow wires to run from the breadboard to the sensors (wire entry points circled in green).

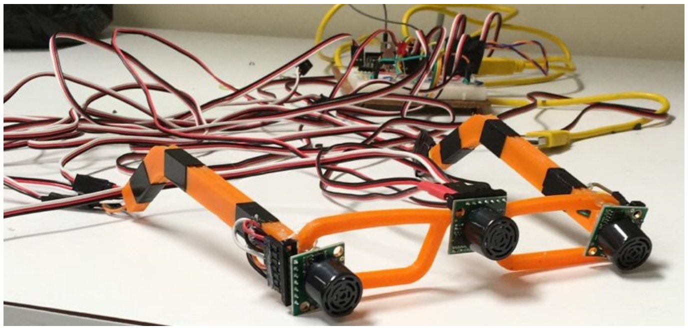

Figure 33: Front view of first iteration of casing

Some important lessons were learnt from this casing iteration. Firstly, it was clearly visible that a third sensor was not a viable options due to the base of the sensor PCB hitting the bridge of the user's nose. Another mistake that we were able to identify in our design was the use of hollow tubes that increased the thickness of the frames significantly. This made the glasses heavy and uncomfortable to wear as they did not sit well on the ridge of the user's ear.


Figure 34: Front angled view of second iteration of casing

***Second Iteration Casing:***
By the time this second iteration was made, our communication modules had been added to the BAT. Therefore, the wires seen in the previous iteration were no longer necessary. Some other components such as potentiometer and a button were also added to our design. Further details about these modifications are given in the following chapter.

As seen in Figure 36, the left and right frames were made with different size cube-shaped buckets attached to them. The first bucket (labeled 1) housed the protoboard containing the microcontroller, wireless transceiver and the rest of the majority of the circuitry. The second bucket (labeled 2) held the 3.7V battery. The sensors were placed on the right and left edges of the front frame and held in place with hot glue. The wires connected to the sensor were fed through the narrow slits on each side of the front frame (labeled 5) and passed through the larger hole (labeled 4) so that they could be connected to the main board. The larger hole was used to make the the button accessible to the user. The smaller holes on the floor of the first bucket (labeled 3) were added to allow users to access the two potentiometers.

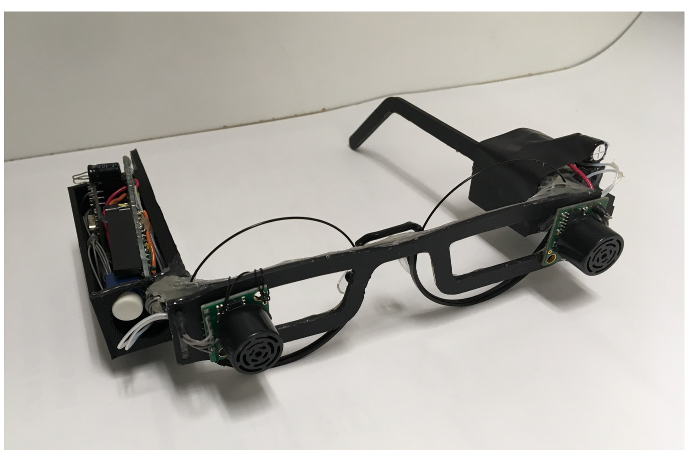

Figure 35: Isometric view of second iteration of casing

From this design, we were able to identify some major areas for improvement. For one, the angle of the nose bridge was too wide which resulted in the glasses slowly sliding down the user's nose. It was decided that in future designs the nose angle would be modeled of lab safety glasses which have a bridge width of around 18 in (Grainger, 2015). It was also noted that from an aesthetic standpoint the first bucket was too large, therefore future iterations would need a smaller PCB so that the bucket could be reduced.

***Third Iteration Casing:***

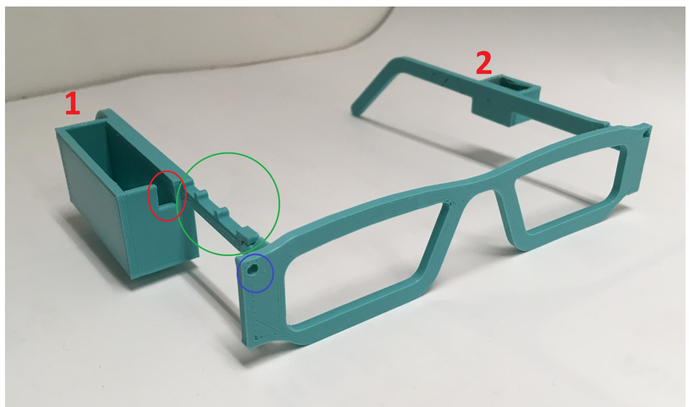


Figure 36: Isometric view of third iteration of casing

In the third iteration, the weaknesses in the previous iteration design were addressed. The large buckets on either side of the glasses were reduced significantly (labeled 1 and 2 in Figure 36). The potentiometers and button were removed from inside the bucket and moved to the right frame (circled in green) to make them more accessible. The narrow slits on either side of the glasses were replaced with holes. Finally, the bridge width was reduced to ensure that the glasses didn't slide down.

In this iteration, we found that the bridge needs to be reduced even more than it already had been. To accommodate the potentionmeters and button, the first bucket was moved further back towards the user's ear which made the design less comfortable. These issues were fixed in the final iteration which served as the casing for our final product. That casing is explained in the following chapter.

# 4 Systems Level Device Description

## 4.1 Hardware Architecture

The two main circuits comprising the hardware for the BAT device are the glasses and band circuits. Referring to Figure 17, the glasses circuit is the implementation of the purple "Glasses" block. The main functionality of this circuit is to record sensor information, convert it to appropriate vibrating patterns, and send this information to the vibrating bands. The band circuit is the implementation of the orange "Vibrating Bands" blocks which receives the vibrating pattern data from the glasses. These pattern values are then used to vibrate a motor. In this way, proximity information received at the glasses is correlated to vibrations at the bands. A deeper look at each circuit is given below.

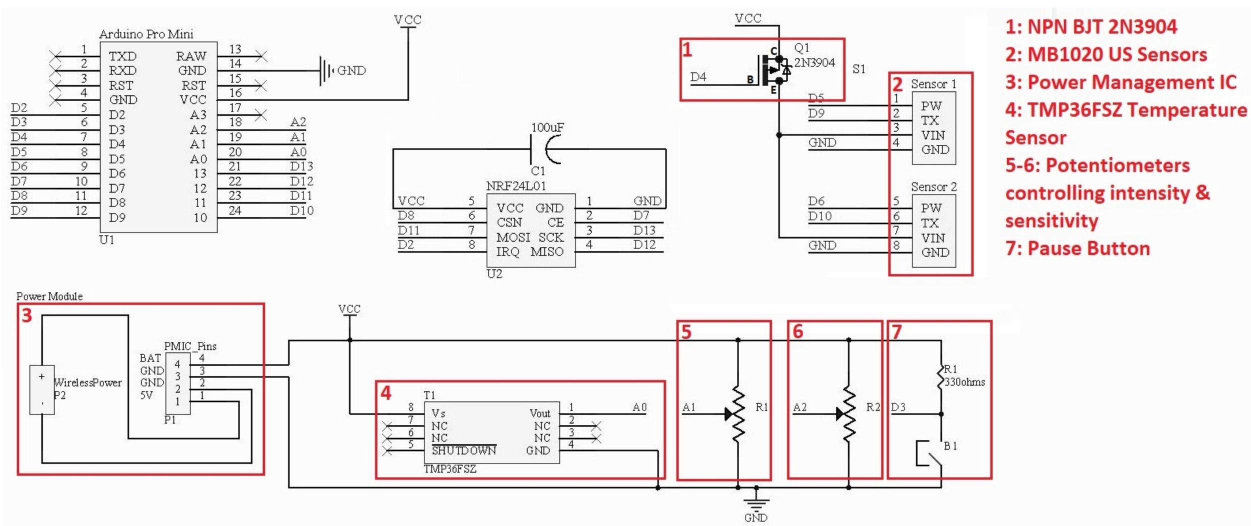


Figure 37: Final glasses system circuit

Starting off with the glasses circuit, the modules that were mentioned in the "Product Development" section including the ultrasonic sensors, temperature sensor, and the 2.4GHz transceiver were integrated into a single circuit with relative ease. Some additional components were added including two potentionmeters, a button, and an NPN transistor. The potentiometers were added to control the sensitivity and maximum vibration intensity of the bands. The button and transistor were used to pause the vibrations and put the whole system into low power mode. Once the button is pressed, the transistor switch cuts the power to the whole system. This feature was added to allow the user to turn off the device when entering an environment that they are familiar with. The reasoning behind this decision was that in such environments the vibrations might be unnecessary or even distracting. An additional benefit of this is the reduced power consumption while the device is in low power mode.

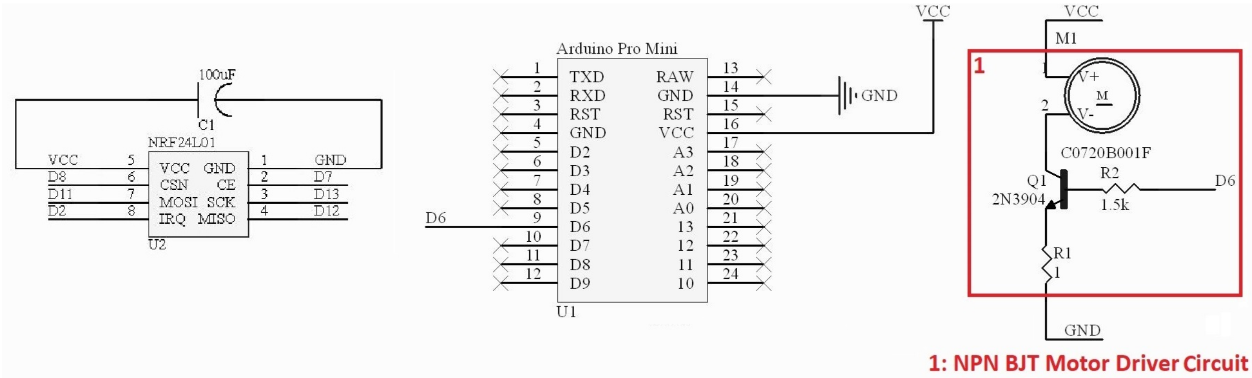


Figure 38: Final band system circuit

For the band circuit, the components remained unchanged from when the motor was tested separately. The majority of changes in the band unit were in the software rather than in the hardware.

A total of three PCBs were made based on the two circuits comprising the BAT system. The first circuit, shown in Figure 37, was divided into two PCBs. One PCB contained the microcontroller, the communication module and a BJT to cut the power lines. The second board contained the user adjustable features including the two potentiometers for adjusting sensitivity and intensity of vibration and the pause button. Additionally, this board hosted the power management module and coil for wireless charging. The two boards were linked together through board connectors.

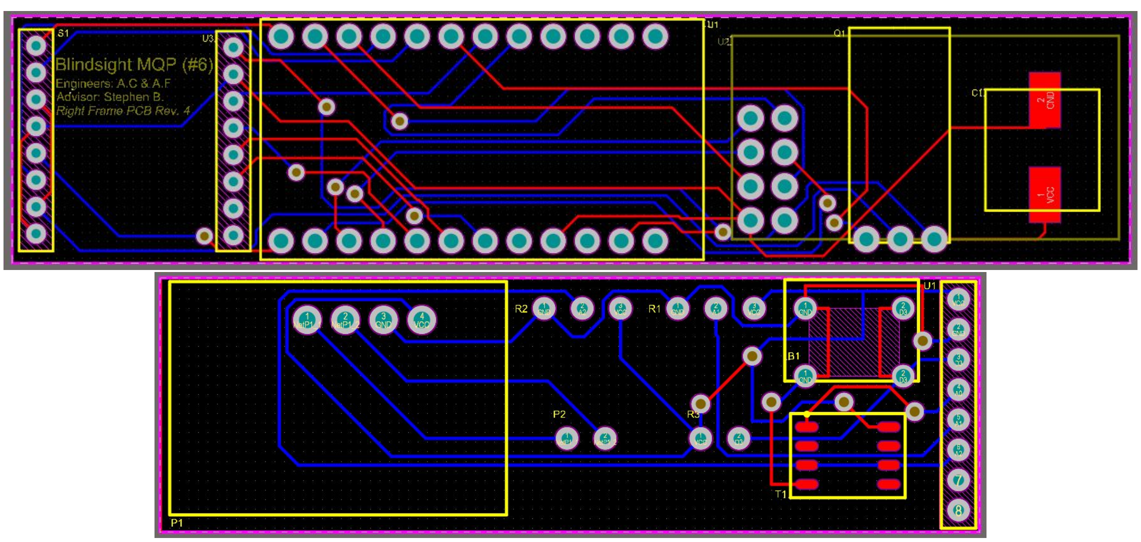


Figure 39: From top to bottom (a) Board containing MCU and Communication Module (b) Board containing user adjustable features

The third PCB, created based on the circuit shown in Figure 38, was placed in the bands and was used to collect proximity information wirelessly sent from the glasses PCB and then drive the motor accordingly.

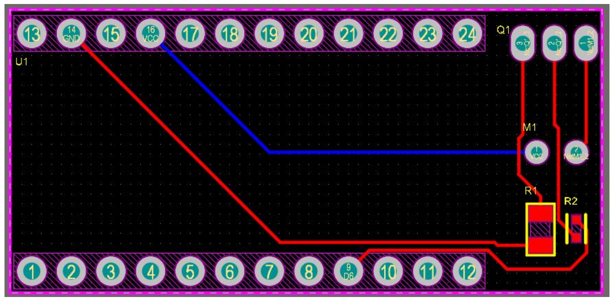

Figure 40: Board containing MCU, Communication Module and Motor Driver Circuit

## 4.2 Software Architecture

### 4.2.1 High Level Software Overview

The software for Blindsight is divided into a package that controls the transmitter and a second that controls the receivers. The transmitter package includes code to control the sensing, calibration, user input and communications. The receiver package is mainly composed of communications code and the necessary controls for the motor vibration. The calculation of the vibration intensity and sensitivity is performed at the master.

### 4.2.2 Sensing

The MB1020 ultrasonic sensor modules require a short 25uS pulse to begin their ranging sequence. In the selected configuration, the master pulses one sensor and waits for the sensor to finish reporting its distance measurement. Once the sensor returns a measurement, the master pulses the second sensor. The measurement of the pulse width is done using the PulseIn function which enters a while loop until the selected pin changes states. This results in no other instruction executing until a pulse is received. This configuration arises from the limited availability of interrupt pins in the AtMega328P. Using an interrupt pin to detect the rising and falling edges of the distance measurement would result in more real-time performance as the processor continues executing instructions in the background while it waits for the sensor to complete its measurement.

### 4.2.3 Pause

The pause button allows the user to momentarily pause the operation of the device. Upon pressing the pause button, the system enters low power mode. Since the pause button must

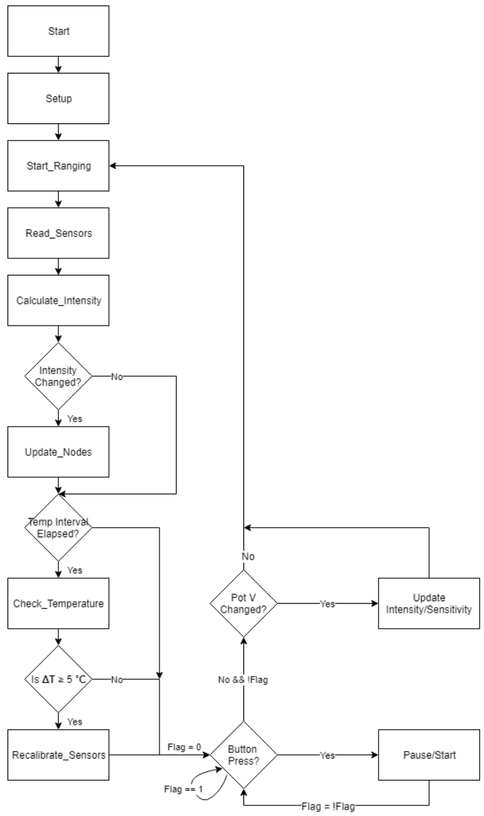


Figure 41: Visual representation of how our code flows through different functions and states

be able to interrupt the operation of the device at any time, it is handled using an external interrupt. According to the documentation for the ATmega328P, there are two pins that are enabled for external interrupts: D2, D3. Since pin 2 is used by the NRF24, the momentary push-button is connected to pin 3. The pin is externally pulled-up with a resistor such that pressing the button brings the potential at the pin to ground.

When the button is pressed, the processor immediately jumps to the assigned handler function for the interrupt. The ISR simply inverts the current state of the device, which is stored in a global boolean. The button is debounced using a simple delay which checks that the logic level at the pin is the same after a number of milliseconds.

```
void PAUSE_ISR(){
  lastDebounce = micros();
  while(micros() - lastDebounce < 5000){
    lastDebounce = micros();
  }
```

```
    if(PAUSE_PIN) {
      blindsight_running = !blindsight_running;
    }
  }
```

Upon exiting the ISR, the code executes the necessary commands to place the processor in low power mode.

```
  void low_power_mode(){
    for (byte node = 0; node < NUMBER_OF_SENSORS; node++) {
      radio.openWritingPipe(nodeAddresses[node]);
      bool tx_sent;
      int LPM = 999;
      tx_sent = radio.write(&LPM, sizeof(LPM));

      if (tx_sent) {
        if (radio.isAckPayloadAvailable()) {
          radio.read(&remoteNodeData[node], sizeof(remoteNodeData[node]));

        } else {
          ;;
        }
      } else {
          ;;
      }
    }

    // Wait until PAUSE button is released before entering LPM
    while(digitalRead(PAUSE_PIN) == LOW){
      ;;
    }
    radio.powerDown();
    attachInterrupt(1, PAUSE_ISR, LOW);
    LowPower.powerDown(SLEEP_FOREVER, ADC_OFF, BOD_OFF);
    detachInterrupt(1);
    radio.powerUp();
    }
```

The low power mode sequence first commands both slave nodes to sleep. Once the nodes acknowledge the receipt of their commands, the interrupt is attached to the Pause pin again and the device enters ultra low power mode. In this mode all oscillators are off and the only way to wake the device is through the external trigger generated by the Pause pin.

When the user presses the pause button, the device immediately continues the execution of the function, detaches the interrupt, and begins ranging again. The interrupt is not re-attached until a few seconds have elapsed and the button is no longer pressed. These two conditions are included to stop erratic behavior if the user were to hold down the button to turn the device on or if he were to press the button multiple times in a row.

```
if(millis() - last_pause > 5000 &&
        !pause_interrupt_set &&
        digitalRead(PAUSE_PIN) == HIGH)
{
  attachInterrupt(1, PAUSE_ISR, LOW);
  pause_interrupt_set = true;
}
```

### 4.2.4 Sensitivity Adjustment

The device is intended to accommodate to the widest possible range of users. This requirement means that the device must accommodate the gait of people of different heights. Since a taller person will reach an object in less steps than a shorter person, it is expected that the taller individual may want the device to start detecting obstacles that are slightly further away than the shorter individual might find necessary. This change in sensitivity is achieved by selecting the detection distance using a potentiometer. Although the detection distance of the utrasonic sensors is 6 meters, a hard limit is placed at 2 meters. The user may adjust the detection distance within the 2 meter limit. For comparison, the range of detection of the long cane is approximately 1.2 meters.(Pyun, Kim, Wespe, Gassert, & Schneller, 2013).

### 4.2.5 Intensity Adjustment

$$Intensity = 255 - \frac{(ADCValue - MinADCValue)}{(MaxADCValue - MinADCValue)} * 255, \tag{3}$$

In order to accommodate for comfort, the user is given the option to adjust the intensity of the vibrations. The vibration intensity may be adjusted using a potentiometer. This adjustment will change the intensity for all three buckets at the same time. The code below generates the command that is sent to the vibrating modules. The first three digits represent the vibration intensity and the next three the period of the pulses. The period ranges from 0 to 1/4 depending on the distance to the obstacle.

```
// construct package
if(pulseList[i] < MIN_DISTANCE){
  //Serial.println("High");
  newIntensity = range_intensity*1000+250;
}else if(pulseList[i] < MED_DISTANCE){
  //Serial.println("Mid");
  newIntensity = range_intensity*1000+333;
}else if(pulseList[i] <= MAX_DISTANCE && pulseList[i] > MED_DISTANCE){
  //Serial.println("Low");
  newIntensity = range_intensity*1000+500;
}else{
  //Serial.println("No");
  newIntensity = NO_INTENSITY*1000+111;
}
// set update flag
if(intensityList[i] != newIntensity) {
    intensityList[i] = newIntensity;
    update_flag = 1;
 }
```

Through experimentation, it was determined that the selected vibrating motors generated noticeable vibrations in the 105-255 PWM range. At lower values, the motors no longer vibrate. Therefore, it is necessary to cap the minimum PWM value at 105, which is done at the receiver using the following logic:

```
received_pwm_setting = (dataFromMaster - (dataFromMaster % 10)) / 10;
min_pwm_setting = 105;
pwm_setting = (received_pwm_setting < min_pwm_setting) ? ...
    received_pwm_setting : min_pwm_setting;
```

### 4.2.6 Communication

Communication between the slave and master modules is achieved using a star network of NRF24 modules. Each slave is assigned an address within the same channel. In this configuration, all the slaves receive the same data packets, but disregard any packet that is not addressed to them.

In order to communicate with the receivers, the master establishes a channel to which it will write and the receivers will listen to. Within the channel, the master opens a writing pipe for each receiver. A single pipe is open at any one time and it basically represents a specific receiver address. Each receiver listens to its own pipe. This means that all the receivers will receive the same packages, but they will only pay attention to those packages that are addressed to them. In other words, they will only listen to the package that is in their own pipe. The master sends a message and awaits an automatic acknowledgement of receipt from the receiver. If it does not receive acknowledgement, an error is produced and the master continues to the next receiver.

```
void Blindsight_Library::update_nodes(){
    for (byte node = 0; node < NUMBER_OF_SENSORS; node++) {
        radio.openWritingPipe(nodeAddresses[node]);
        bool tx_sent;
        tx_sent = radio.write(&intensityList[node], sizeof(intensityList[node]));
        if (tx_sent) {
          bool ackavailable = radio.isAckPayloadAvailable();
          if (ackavailable) {
            radio.read(&remoteNodeData[node], sizeof(remoteNodeData[node]));
          } else {
            Serial.println("[DBG] No ack packet available");
          }
        } else {
          Serial.print("[Err] The transmission to the selected node failed:");
          Serial.println(node);]
        }
    }
}
```

### 4.2.7 Calibration

According to MaxBotix, their MB1020 Ultrasonic Sensors must undergo recalibration if there is a 5 °C change in ambient temperature. The recalibration adjusts the sensor's ringdown pattern. Ringdown refers to the resonance of the air which can cause misreadings by the sensors. If the ambient temperature decreases, the sensor will experience reduced close range sensitivity. At a higher temperature, there would be reduced long range sensitivity. Given the drastic changes in temperature between indoors and outdoors due to air conditioning, it is important for the device to maintain the sensors calibrated to avoid misreadings. Recalibration of the sensors is achieved by cycling their power and triggering a reading cycle. The following functions verify if recalibration is necessary and execute the recalibration cycle.

```
bool Blindsight_Library::check_temperature(){
  int t_check = false;
  float actual_temp = (((analogRead(TEMP_SENSOR_PIN) * 5.0)/1024.0)-0.5)*100;

  if (abs(actual_temp - calibration_temperature) >= 5.0){
    calibration_temperature = actual_temp;
    t_check = true;
  }
  return t_check;
}

void Blindsight_Library::recalibrate_sensors(){
  digitalWrite(SENSOR_POWER_PIN, 0);
  delay(50); // Small delay to allow sensors to power down
  digitalWrite(SENSOR_POWER_PIN, 1);
  delay(250); // Delay 250ms for the power-up delay
  start_ranging();
  read_sensor();
}
```

The power rails of the sensors are controlled using a transistor. The transistor is necessary in order to cycle power to the rails during recalibration. Refer to the module integration section for a description of the circuit used to monitor the temperature.

### 4.2.8 Haptic Feedback

As discussed earlier, the vibrating bands will pulse at a rate proportional to the range from the obstacle. The sensing distance is broken up into four buckets, each of which correspond to a different pulse rate. The pulse rate information is obtained by the receivers as the last three digits in the packet sent by the master. The master sends a packet that is formatted in the following manner:

$$concatenate(3\_digit\_pwm\_value, 3\_digit\_period)$$

The three digits at the end of the packet correspond to the period in milliseconds. The first three digits are used to configure the PWM value to vibrate the motors. This results in three possible periods for the pulsing of the device, all of which vibrate with the same intensity. In a previous iteration of the algorithm, the PWM value of each bucket changed independently resulting in a constant vibration with different intensities depending on the distance to the obstacle.

The pulsing of the vibration is achieved using a timer interrupt. The timer is set to overflow and trigger an interrupt. Since the interval of the interrupts is considerably lower than the desired period, the ISR contains a counter that keeps track of the number of interrupts. When enough interrupts have occurred to match the period of the waveform then the rest of the logic executes.

```
void configure_interrupt(){
  OCR2A = 0xFF; // interrupt at 255
  TIMSK2 |= _BV(OCIE2A);
}

ISR(TIMER2_COMPA_vect){
  number_of_interrupts += 1;
  interrupts_per_period = 1000.0*period;

  if(number_of_interrupts > interrupts_per_period){
    number_of_interrupts = 0;
  }else if(number_of_interrupts < interrupts_per_period / 10){
    analogWrite(MOTOR_PIN, pwm_setting);
  }else{
    analogWrite(MOTOR_PIN, 0);
  }
}
```

## 4.3 Casing

The final casing was printed in seven parts. The first four parts were used to assemble the glasses legs and the fifth part was the glasses main frame.

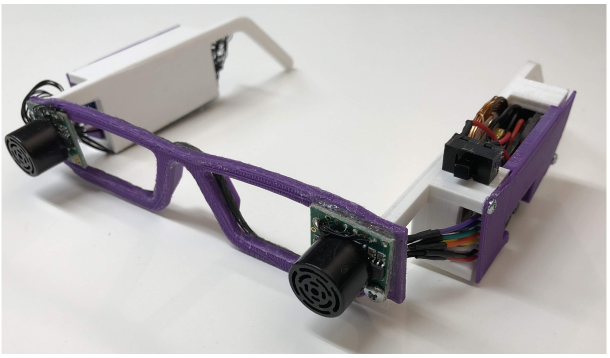

Figure 42: Isometric View of Glasses

The final two parts were used to assemble the wireless charging pad. Parts were connected together with 2-56 x 1/2" machine screws.

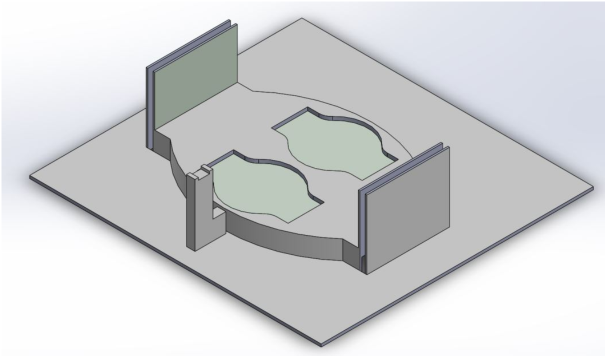

Figure 43: Isometric View of Wireless Charging Pad

An additional two parts were printed to act as clasps for the two bands. A picture of the glasses and the bands placed on the wireless charging pad is shown below.

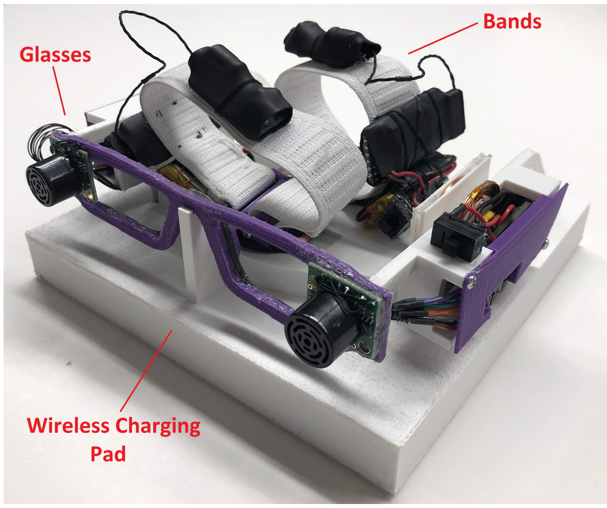


Figure 44: Isometric View of Glasses and the Bands placed on the Wireless Charging Pad

# 5 Device Testing and Results

During the device testing phase of the project, three categories of individuals were selected to provide feedback on our device. The first group was the designers involved in producing the product. As the people most knowledgeable about the device, it was logical that the BAT first be tested by the designers to remove any obvious flaws. The next group that tested the device was individuals with no visual impairments. This group was particularly crucial to ensure that we not only covered disability-specific design but also the basics of general design. Finally, the device was tested with individuals with severe visual impairments who were able to give us insight into problems that blind individuals would face using the BAT.

The benefits of this "funnel approach" was that it started off by making sure that our design process considered features that both sighted and blind individuals would want. This made sure that as designers we avoided design blindspots that would be present if focus was only given to disability-centric features.

The actual testing involved having participants go through a course where they avoided obstacles that frequently caused head-level accidents in common environments. The obstacles that were mimicked in the course included a stop sign, an overextended window sill and an overhanging support structure. All these structures were made from cardboard to minimize the risk of the injury to volunteers participating in the course.


Figure 45: From left to right (a) Overextended window sill (b) Overhanging support structure (c) Stop sign

## 5.1 Testing with Device Designers

Testing was carried out by both designers. The purpose of this testing was to remove any obvious flaws in the basic functionality of the device. The feedback received is given below.

- Speed of device: A lag was observed in preliminary testing.
- Comfort: Nose bridge had some jagged edges that needed to be sanded down.
- Sensor Functionality: The first sensor behaved as expected, however a noticeable lag was observed with the second sensor. Also, a random glitch was observed where the device would get stuck in a vibration pattern despite changes in the proximity of objects from the user.

## 5.2 Testing with Individuals Without Visual Impairments

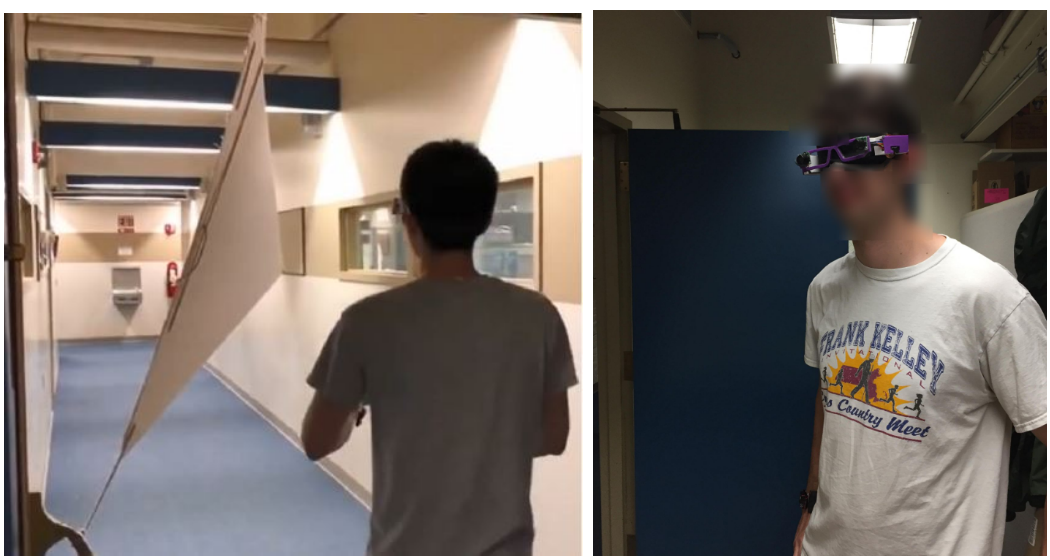


Figure 46: From left to right (a) Sighted individuals participating in course and approaching an overhanging support structure obstacle (b) Sighted individual wearing BAT device

Testing with individuals with no visual impairment proved to be the most beneficial of the three tests that were conducted with the BAT. For this testing, participants wore a blindfold and walked through the course with the BAT device on. Two feedback forms were created prior to testing, a form for organizers to fill out while the participant was walking through the course and a form for participants to fill out after walking through the course. These forms can be found in Appendix B. The suggestions received from participants are summarized below.

- Haptic Feedback: A pulsed vibration was successful in alerting users of the proximity of objects, however participants did complain that it was difficult to differentiate between vibration intensities. The result was that individuals using the BAT had difficulty interpreting how far the object was from them based on the vibration pattern.

- Sensor Functionality: A wider field-of-view was a recommendation from some participants. The conical shape of the FOV resulted in the device not reporting objects that were very close to the face of the individual, but not directly in front of it. This resulted in some participants bumping their shoulder onto the obstacles.

## 5.3 Testing with Individuals With Visual Impairments

The BAT device was presented to the Regional Manager at the Massachusetts Commission for the Blind. As a blind individual, the manager was able to give us very descriptive feedback about areas of improvement in the BAT.

- Haptic Feedback: Continuous vibration was not effective because over time the user starts to drown it out. Pulsed vibrations catch the user's attention more aggressively.

- Speed of device: A one second lag was observed and noted as unacceptably high.

- Comfort: Nose bridge was not tight enough leading to the glasses sliding down the participant's nose. Sharp edges made the device uncomfortable on the ears.

- Aesthetic: Bulkiness and weight of device were noted as unattractive features.

# 6 Conclusion and Recommendations

## 6.1 Recommendations

### 6.1.1 Processor and Sensing

The team recommends that the next iteration of the device is built on the MSP430 platform. The MSP430 offers many advantages over the AtMega328P, especially when it comes to power consumption. The MSP430 also offers a larger number of interrupt enabled pins which would allow for a more responsive design of the software. As discussed in the software architecture section, the processor currently idles for up to 50ms while it waits for each sensor to capture a pulse. With more interrupt enabled pins it could be possible to allow the processor to execute background tasks such as updating the bands or calculating vibration intensities while the sensors range. It is also recommended that a new sensor is identified. The MB1020 is relatively large and this results in difficulties for designing a visually appealing frame for the glasses. The MB1020 also outputs the pulse information in multiple formats which adds to the 50ms capture time. According to the datasheet, the pulse is captured within 39mS (MaxBotix, 2015). The addition of the RS232 output adds 10ms to the timing sequence. In a device that must produce close to real-time performance, unnecessary delays such as these should be eliminated. Alternatively, the ultrasonic sensor can be replaced altogether with a solid state LiDAR technology which provides a higher resolution of the surroundings. One last disadvantage of the ultrasonic sensor, which was identified during testing, is that since the detection region is a cone objects disappear from the field of view as the user gets close to them. This could result in the user's head avoiding the obstacle while the shoulders still impact the obstacle.

### 6.1.2 Frame Design

There are obvious improvements to be made in the design of the frames, particularly in the attractiveness of the design. With smaller sensors and batteries, the task of designing a more visually appealing frame will be easier. It is important to strive to eliminate all sharp edges and to carefully examine the design of the nose bridge since it is the area that brings the greatest discomfort to the user.

### 6.1.3 Alternative Form Factors

Next, the team recommends that other form factors for the sensing module are evaluated. This would allow for the device to be more inclusive as it could adapt better to the preferences of the user. During testing it was found that users who have never used glasses found the current design exceedingly uncomfortable as would any first time user of optical glasses. For these users in particular, a different form factor may be preferable.

## 6.2 Conclusion

The design of the a proximity sensing device that employs wireless haptic feedback was challenging and the results were mixed. The BAT device met, at a basic level, the specifications that were outlined during the conception of the design including wireless feedback, wireless charging and an aesthetic-focused design. However, feedback from blind users suggested that the device has a long way to go before becoming a viable option for reducing head-level accidents. Further work in developing an effective way to convey obstacle proximity through vibrations is crucial in order for Blindsight to meet its intuitive design goals. The key takeaway from the design of this mobility aid was the importance of a design centric approach which has the Seven Principles of Universal Design at its core. Adhering to this design philosophy as well as to the iterative design approach resulted in a device that met the needs of the target population better than existing products. We recommend that any team that desires to develop a disability aid places these design philosophies at the core of their development from the conception of the idea to increase the chances of success with their device. Most significantly, this project laid the framework for future projects on the development of disability aids, especially for blind individuals.

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# Appendix

## A Sensor Testing Data

*All units are in millimeters*

***VL53L0X Testing:***

Table 8: Round 1 VL53L0X Sensor Data Indoors

| Expected Distance | *Left Sensor* | *Middle Sensor* | *Right Sensor* | Line of Identity |
|---|---|---|---|---|
| 250 | 217 | 204 | 199 | 250 |
| 500 | 467 | 438 | 449 | 500 |
| 750 | 725 | 699 | 706 | 750 |
| 1000 | 962 | 868 | 946 | 1000 |
| 1250 | 1236 | ** | 1201 | 1250 |
| 1500 | ** | ** | ** | 1500 |
| 1750 | ** | ** | ** | 1750 |

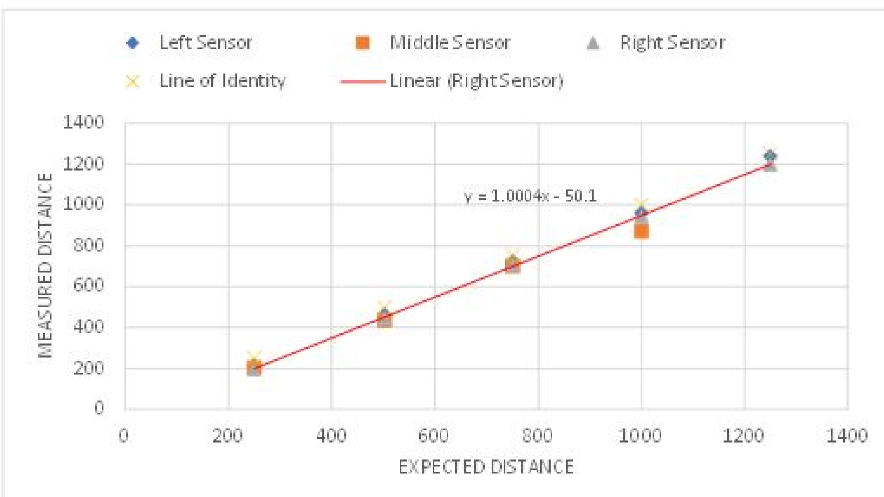


Figure 47: Comparing round 1 indoors VL53L0X sensor data linear regression line to the line of identity

Table 9: Round 2 VL53L0X Sensor Data Indoors

| Expected Distance | *Left Sensor* | *Middle Sensor* | *Right Sensor* | Line of Identity |
|---|---|---|---|---|
| 250 | 261 | 262 | 272 | 250 |
| 500 | 458 | 447 | 471 | 500 |
| 750 | 709 | 623 | 714 | 750 |
| 1000 | 1,017 | 857 | 1012 | 1000 |
| 1250 | ** | ** | ** | 1250 |
| 1500 | ** | ** | ** | 1500 |
| 1750 | ** | ** | ** | 1750 |

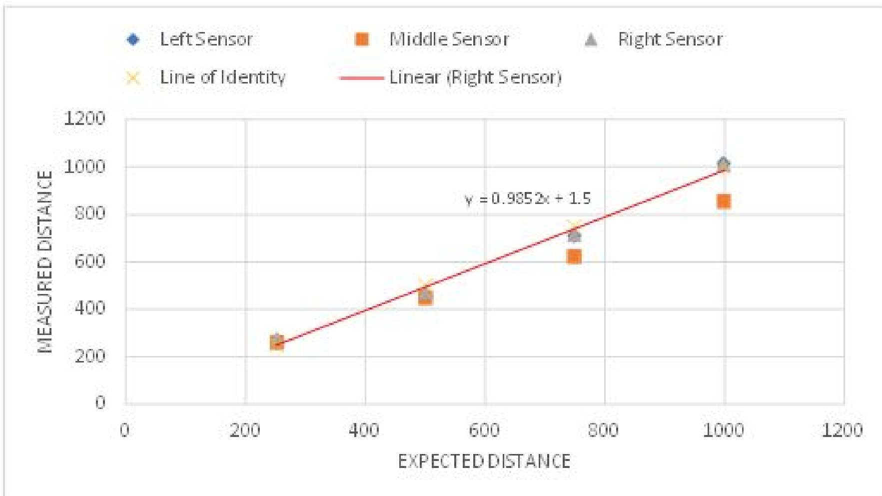


Figure 48: Comparing round 2 indoors VL53L0X sensor data linear regression line to the line of identity

Table 10: Round 3 VL53L0X Sensor Data Indoors

| Expected Distance (m) | *Left Sensor* | *Middle Sensor* | *Right Sensor* | Line of Identity |
|---|---|---|---|---|
| 250 | 243 | 257 | 258 | 250 |
| 500 | 444 | 462 | 456 | 500 |
| 750 | 728 | 740 | 736 | 750 |
| 1000 | 995 | 1012 | 1004 | 1000 |
| 1250 | 1213 | 1230 | 1221 | 1250 |
| 1500 | ** | ** | ** | 1500 |
| 1750 | ** | ** | ** | 1750 |

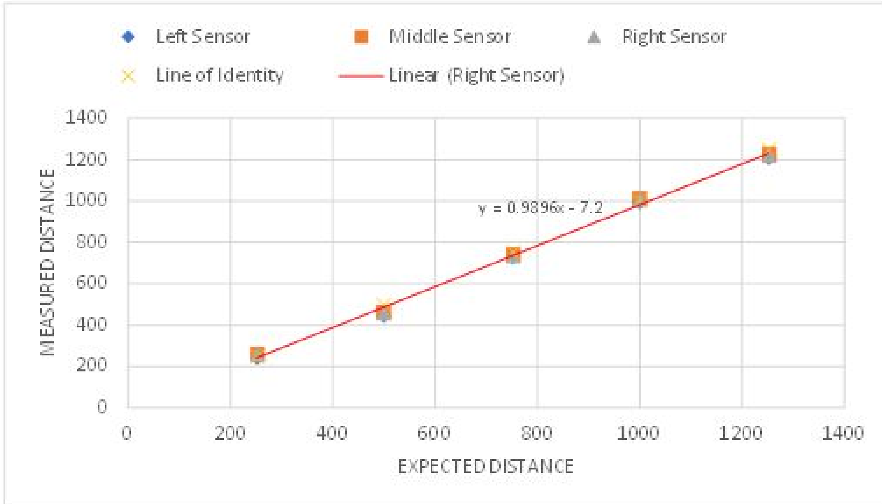


Figure 49: Comparing round 3 indoors VL53L0X sensor data linear regression line to the line of identity

*Temperature during outdoors testing was 1°C*

Table 11: Round 1 VL53L0X Sensor Data Outdoors

| Expected Distance (m) | *Left Sensor* | *Middle Sensor* | *Right Sensor* | Line of Identity |
|---|---|---|---|---|
| 250 | 188 | 194 | 199 | 250 |
| 500 | 388 | 394 | 398 | 500 |
| 750 | 650 | 684 | 660 | 750 |
| 1000 | 905 | 906 | 924 | 1000 |
| 1250 | 1204 | 1199 | 1216 | 1250 |
| 1500 | ** | ** | ** | 1500 |
| 1750 | ** | ** | ** | 1750 |

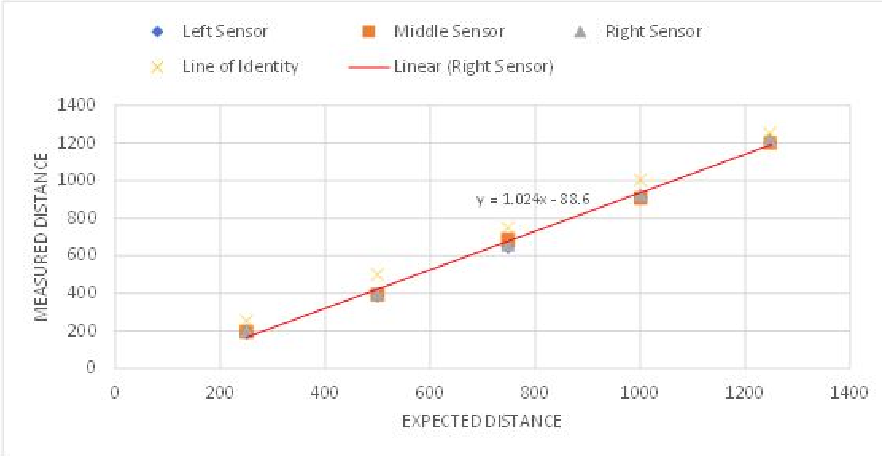


Figure 50: Comparing round 1 outdoors VL53L0X sensor data linear regression line to the line of identity

***MB1020 Testing:***

Table 12: Round 1 MB1020 Sensor Data Indoors

| Expected Distance (m) | *Left Sensor* | *Middle Sensor* | *Right Sensor* | Line of Identity |
|---|---|---|---|---|
| 0.25 | 0.93 | 0.929 | 0.928 | 0.25 |
| 0.5 | 2.146 | 2.437 | 2.438 | 0.5 |
| 0.75 | 3.912 | 3.894 | 3.902 | 0.75 |
| 1 | 5.234 | 5.354 | 5.216 | 1 |
| 1.25 | 6.411 | 6.523 | 6.537 | 1.25 |
| 1.5 | 8.019 | 8.127 | 8.144 | 1.5 |
| 1.75 | 9.486 | 9.585 | 9.493 | 1.75 |
| 2 | 10.802 | 10.877 | 10.921 | 2 |
| 2.25 | 12.163 | 12.188 | 12.238 | 2.25 |
| 2.5 | 13.883 | 13.795 | 13.7 | 2.5 |
| 2.75 | 14.721 | 14.797 | 14.762 | 2.75 |
| 3 | 14.753 | 14.812 | 14.757 | 3 |
| 5.791 | 14.76 | 14.815 | 14.801 | 5.791 |

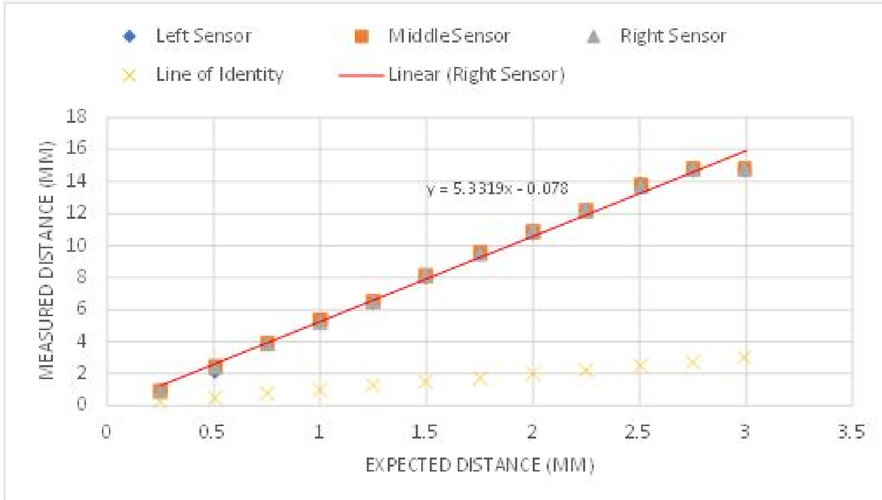


Figure 51: Comparing round 1 indoors MB1020 sensor data linear regression line to the line of identity

Table 13: Round 1 MB1020 Sensor Data Outdoors

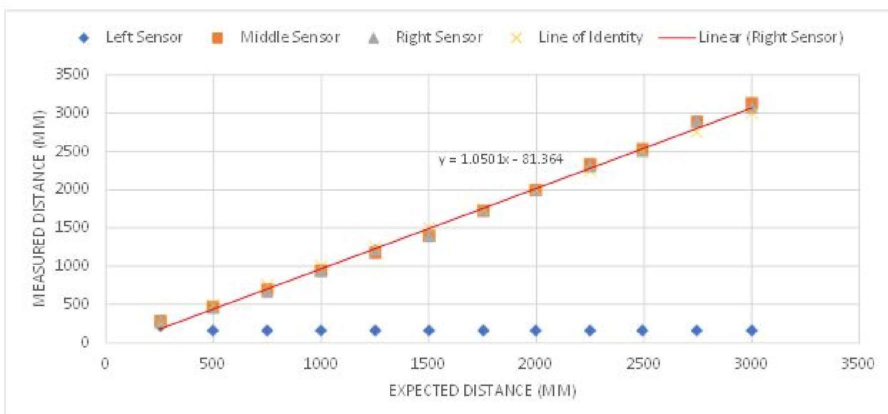


Figure 52: Comparing round 1 outdoors MB1020 sensor data linear regression line to the line of identity

# B Feedback Forms for Testing with Sighted Individuals

***Organizers Feedback Forms:***

1. **Number of objects hit**

2. **Type of objects hit**
*Check all that apply.*
- [ ] Overhanging support structure
- [ ] Overextended window sill
- [ ] Sign post
- [ ] Other: __________

3. **Observed response time** *

4. **Droopiness of device on participant's nose**

5. *Mark only one oval.*
- ( ) Option 1

6. **How much participants struggled to wear glasses and bands?**
*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Not at all | ( ) | ( ) | ( ) | ( ) | ( ) | A lot |

7. **Other observations**

**Other Feedback**

***Participants Feedback Forms:***

1. **Height**

2. **What do you think our device does?**

3. **How much lag time did you observe?**

4. **On a scale of 1 to 5, how heavy were the glasses?** *

   *Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Very light | ◯ | ◯ | ◯ | ◯ | ◯ | Very heavy |

5. **On a scale of 1 to 5, how comfortable did you find the glasses?**

   *Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Didn't know they were there! | ◯ | ◯ | ◯ | ◯ | ◯ | Very uncomfotable |

6. **On a scale of 1 to 5, how difficult did you find to correlate the intensity of vibration with distance from an object?**

   *Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Intuitive | ◯ | ◯ | ◯ | ◯ | ◯ | Very challenging |

7. **Suggestions for improvements?**

**Other Feedback**

# C Cost of Components

Table 14: Component List

| Component | Quantity | Unit Cost (per 1000) | Total Cost |
|---|---|---|---|
| Ultrasonic Sensor - MB1020 | 2 | $17.56 | $35.12 |
| Temperature Sensor - TMP36FSZ | 1 | $1.29 | $1.29 |
| Potentiometer 20kOhm - 3352T | 2 | $1.00 | $2.00 |
| Tactile Switch - CKN90 | 1 | $0.09 | $0.09 |
| Transceiver - NRF24L01 | 3 | $2.09 | $6.27 |
| NPN BJT - 2N3904 | 2 | $0.04 | $0.08 |
| Lithium Polymer Battery - LP552 | 3 | $6.95 | $20.85 |
| Arduino Pro Mini - ATMega328 3.3V | 3 | $9.95 | $29.85 |
| Board Connectors | 1 | $7.99 | $7.99 |
| USB LiPo Charger - MCP73831 | 3 | $6.95 | $20.85 |
| ST Vibrating Motor - ST3160 | 2 | $1.44 | $2.88 |
| Wireless Charging Boards and Coil | 2 | $9.95 | $19.90 |
| SMD 100uF Capacitor | 3 | $0.23 | $0.69 |
| SMD 1.5kOhm Resistor | 2 | $0.06 | $0.12 |
| SMD 1kOhm Resistor | 2 | $1.44 | $2.88 |
| | | **TOTAL** | **$148.09** |