EYERIS: ULTRASONIC/HAPTIC DEVICE FOR THE VISUALLY-IMPAIRED

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Abstract

As a capstone project for the B.S in Electrical Engineering program, we design a wearable device to help a visually impaired individual navigate city streets, sidewalks, and buildings by sensing obstructions in their immediate vicinity and communicating the wearer's bearing (whether they are facing north, south, etc.). To improve usability, the device takes the form of a vest that can be worn atop clothing, and haptic feedback is used so as not to interfere with the wearer's sense of hearing. An array of ultrasonic rangefinders is employed as obstacle detectors, and vibration motors worn on a belt around the abdomen provide haptic feedback to the wearer.

Contents

1 Introduction

The 21st century has brought a wealth of innovation to the field of medicine; advances in medical sensing enable earlier, more accurate diagnoses of diseases, and prosthetic technologies have likewise improved [1]. But despite their innovation and widespread use, the benefits of these technologies have yet been fully realized for individuals with visual impairments [2]. The most common locomotive aid is still the white cane, a device that has seen little improvement over its decades-long tenure. We see this void as an opportunity to apply what we learned in our undergraduate electrical engineering program to a problem affecting roughly 40 million people worldwide [3].

1.1 Limitations of Existing Technologies

Despite its popularity, the white cane has several limitations. Its feedback is localized, requiring the user to sweep it back and forth while walking. Moreover, it requires the user to physically manipulate the device with one hand, which prevents them from using that hand for other purposes (i.e. using the cellphone, carrying groceries bags in more than one hand, using more than one crutch/walking cane, etc.). Finally, it requires a sufficient amount of training as well as dexterity to use well and effectively, which is a deterrent to relying on the white cane as a means to be mobile for many people [4].

We envision a hands-free, wearable solution that provides a circumferential sense of the user's immediate surroundings. Unlike the white cane, this device will continuously sense obstructions in multiple directions in the horizontal plane, leaving the user's hands free. As this device provides a coarse view of the user's surroundings, it is not designed to be used alone; rather, this device will supplement the white cane, whose precise but directional feedback complements the low resolution of our device.

1.2 Design

Our proposed solution is a 360-degree ultrasonic sensor system with haptic feedback, shown in Figure 1. It continuously senses the distances of the surrounding objects using sonar technology, and relays information to the user through haptic feedback located on a belt (to model the 360-degree environment for directional feedback). The information will be encoded as higher intensity vibrations for

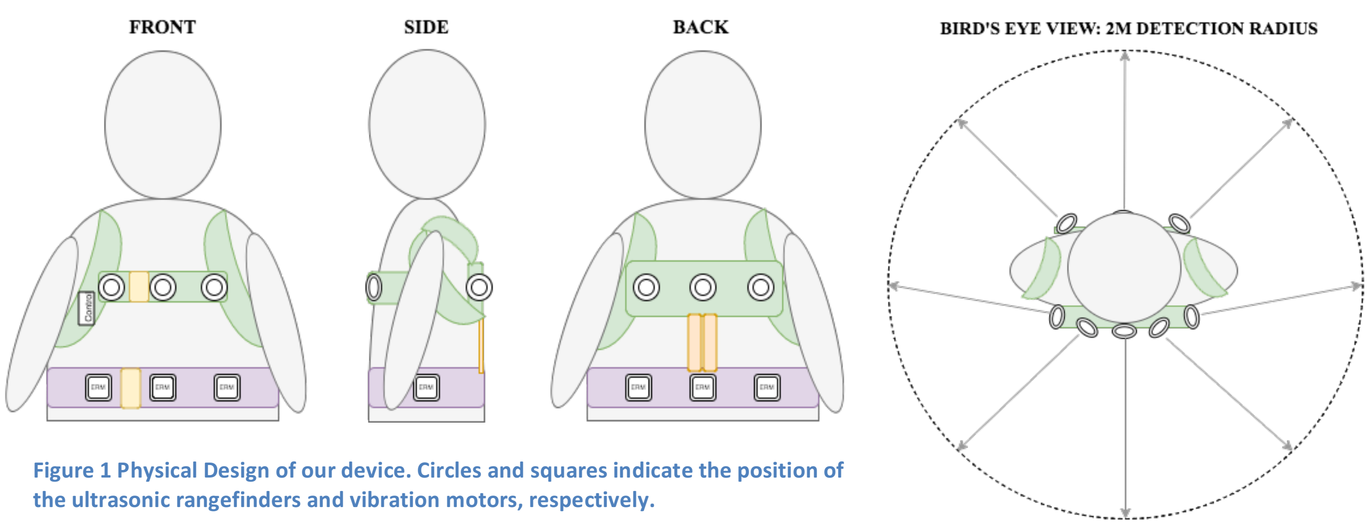


Figure 1 Physical Design of our device. Circles and squares indicate the position of the ultrasonic rangefinders and vibration motors, respectively.

closer objects, and lower intensity vibrations for farther objects. In addition, the haptic belt also provides information about cardinal direction to help the user navigate more easily to their destination. When the user switches on the geomagnetic feedback mode the haptic belt will produce pulsed vibrations on the north side of the body.

1.3 System Level Diagram

At the system level, our device consists of four functional modules, depicted in Figure 2 System block diagram. The power module manages battery safety during charging and discharging, while the sensor and haptic modules provide the system inputs and outputs, respectively. The sensor and haptic module are driven by the control module, which is responsible for running the main program. The power module manages battery safety during charging and discharging, while the sensor and haptic modules provide the system inputs and outputs, respectively. The sensor and haptic module are driven by the control module, which is responsible for running the main program.

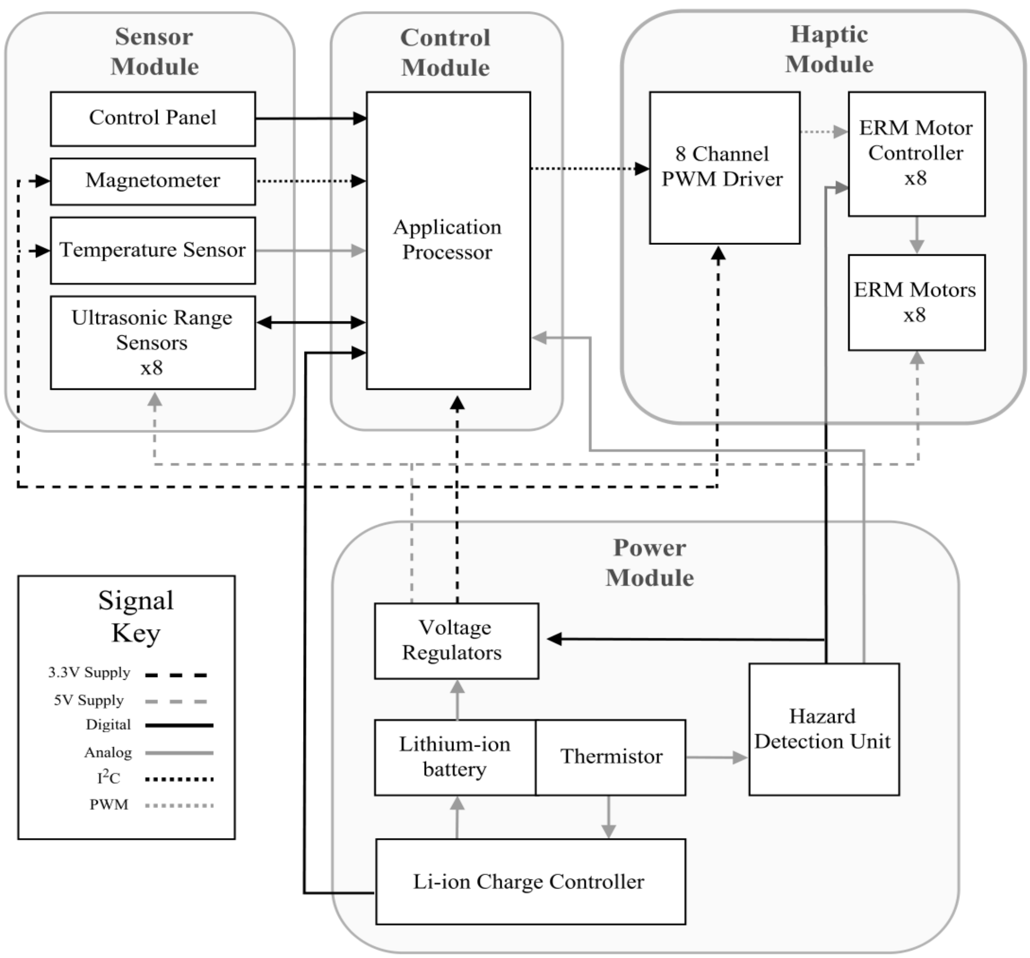


Figure 2 System block diagram.

1.4 Sensor Module

The sensor module includes all components that provide inputs to our system. This includes 8 ultrasonic range sensors, a temperature sensor, a 3-axis magnetometer, and a control panel.

1.4.1 Overall block interface:

Inputs: 5V, 3.3V, control bits from the application processor

Outputs: Digital, PWM, I2C and analog signals to the application processor

1.4.2 Ultrasonic Sensors

The primary data inputs of our wearable device come from the 8 ultrasonic sensors arranged around the torso of the user. Each sensor periodically obtains data about the distance of the closest object, and delivers it to the application processor.

Each sensor has a two-wire external digital interface with active high 5V signaling: one output wire for ultrasonic transmission, and one input wire for detecting a response. To perform a distance measurement, the sensor's transmit pin is pulsed by the application processor for 10µs. The sensor then outputs a series of ultrasonic pulses; when an echo is detected, the sensor drives the receive pin high. These signals are shown in Figure 3. By measuring the delay between the chirp and echo, the application processor can calculate the distance. Measurement and characterization of the ultrasonic can be found in the Design Verification section.

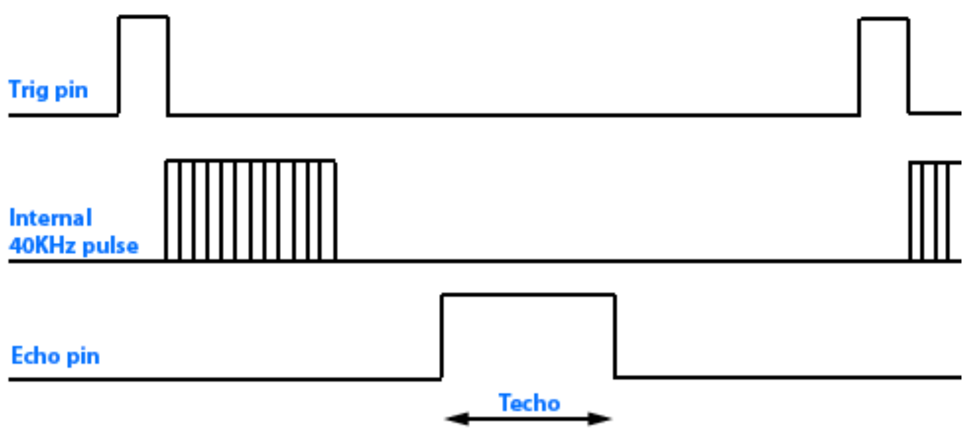


Figure 3 Signal waveforms to perform a signle distance measurement on an ultrasonic sensor

To reduce interference between sensors, the controller will sample one sensor at a time. The outputs of all eight sensors are thus multiplexed into the application processor on one pin to reduce the number of IO pins required to support all 8 sensors.

1.4.2.1 Interface:

Inputs: 5V, 1-bit digital trigger signal from application processor
Outputs: 1-bit digital echo signal to application processor

1.4.3 Temperature Sensor

Because the propagation delay from the sensor to object depends on the air temperature, we also include an analog temperature sensor. This will be read by the application processor using its integrated analog-to-digital converter.

1.4.3.1 Interface:

Inputs: 3.3V

Outputs*:* Analog signal to application processor

1.4.4 Magnetometer

Using a three-axis magnetometer IC enables our device to give absolute orientation feedback to the wearer. The magnetometer will communicate to the application processor using an I2C bus. Because we only include 8 haptic ERMs in our design, our detection of geomagnetic north needs to be accurate to within 22.5°. With 22.5°, we will have enough resolution to activate the correct ERM motor. Additionally, we will be able to know if geomagnetic north lies between two motors and need to activate both.

1.4.4.1 Interface:

Inputs: 3.3V

Outputs*:* I2C bus to application processor

1.4.5 Control Panel

The control panel will contain the master power switch, allow the user to control the modes of operation, and allow the user to adjust the range sensitivity of the ultrasonic sensors.

The control panel will have three push button switches: one to power on/off the wearable device, one to enable geomagnetic feedback, and one to enable proximity feedback. The panel will also have a rotary dial to control the sensitivity of the proximity sensors. The switches will connect to GPIO inputs of the application processor, and the sensitivity potentiometer in the rotary dial will output an analog signal to the application processor that will be interpreted by the integrated ADC.

These switches will be soldered to a simple multi-purpose PC board. It will be contained in an enclosure to ensure protection from the elements.

1.4.5.1 Interface:

Inputs: 5V, power switch (from user), geomagnetic switch (from user), proximity switch (from user), rotary dial (from user)

Outputs: 2 1-bit signals to application processor, 1 analog signal to application processor

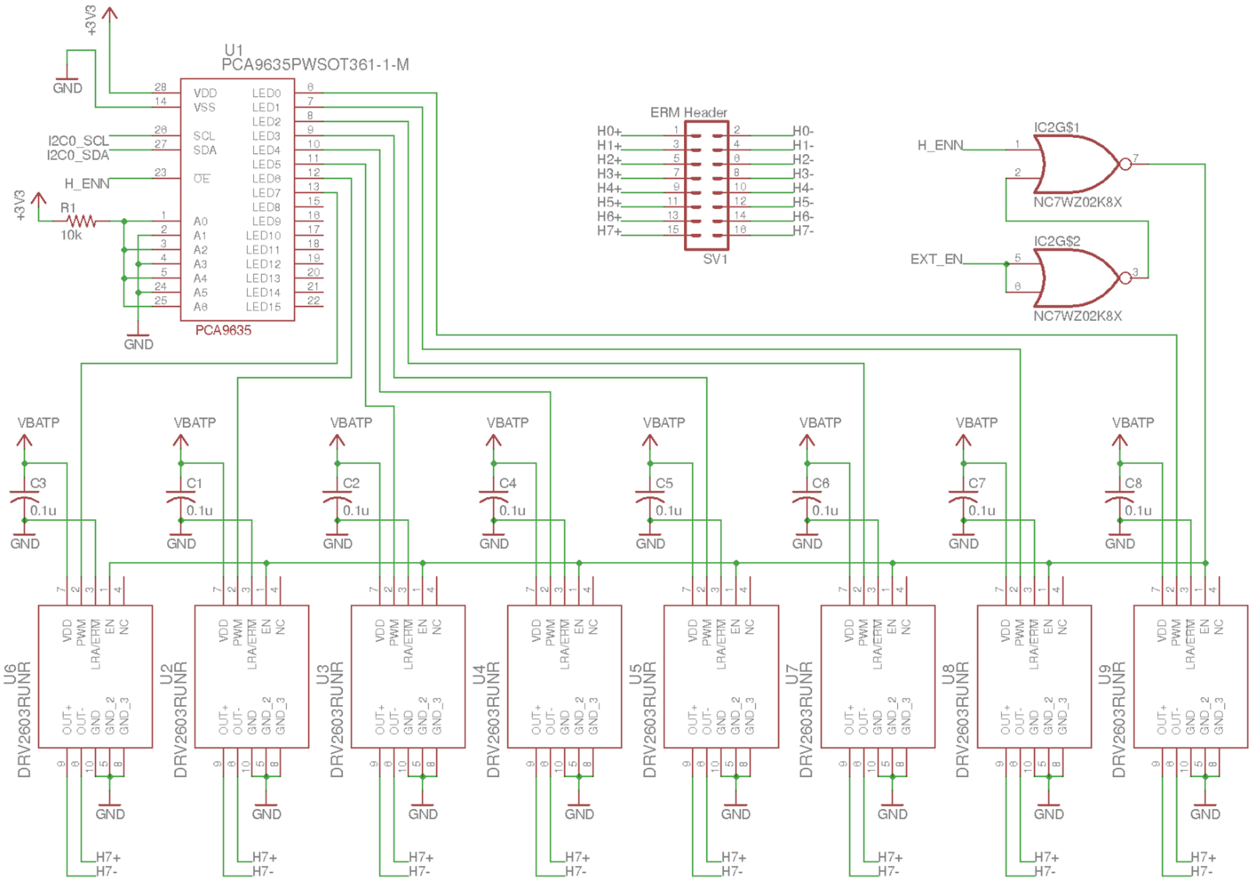


Figure 4 Schematic for the haptic module

1.5 Haptic Module

The haptic module is responsible for generating all haptic feedback to the user. There will be 8 eccentric rotating mass (ERM) modules arranged around a belt worn around the midsection. They are connected as depicted in Figure 4. Each of them will be controlled by an ERM motor controller, and all ERM motor controllers will be controlled by the 8-channel PWM driver. Each component is described in the following sections.

1.5.1.1 Overall block Interface:

Inputs: I2C from the application processor for updating the ERM intensity, 3.3V supply from the power module

Outputs: None

1.5.2 8-Channel PWM Driver

In order to drive the 8 haptic feedback motors with our application processor, we will be using the NXP PCA9635PW to provide 8 free-running PWM 3.3V channels for controlling the 8 haptic motor drivers. The PWM duty cycle of each channel is controlled using an 8-bit data register, providing 256 different levels of duty cycle. The PWM frequency is fixed at 97kHz.

The PWM driver supports a 1Mb/s I2C interface, will be programmed using the transaction diagram seen in Figure 5. The IC supports fully programmable 7-bit I2C address, which in our design will be set to 0x1010101. The IC supports an auto increment feature, so all 8 channels can be updated with only 10 Bytes of data.

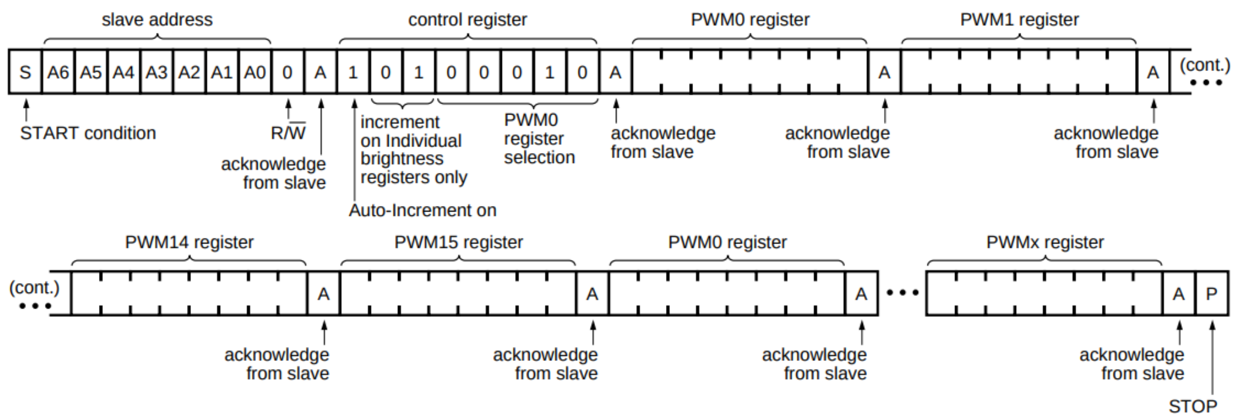


Figure 5 register map for the PCA9635 PWM driver [9]

Interface:

Inputs: 3.3V, I2C from the application processor

Outputs: 8 free-running 3.3V PWM outputs running at 97 kHz

1.5.3 ERM Motor Controller

The 8 ERM motor controllers are used to provide greater control of the ERM intensity. Rather than driving the motors directly with a PWM signal, we are using these controllers because they perform acceleration and active braking. This means the ERM actuators will respond with lower latency.

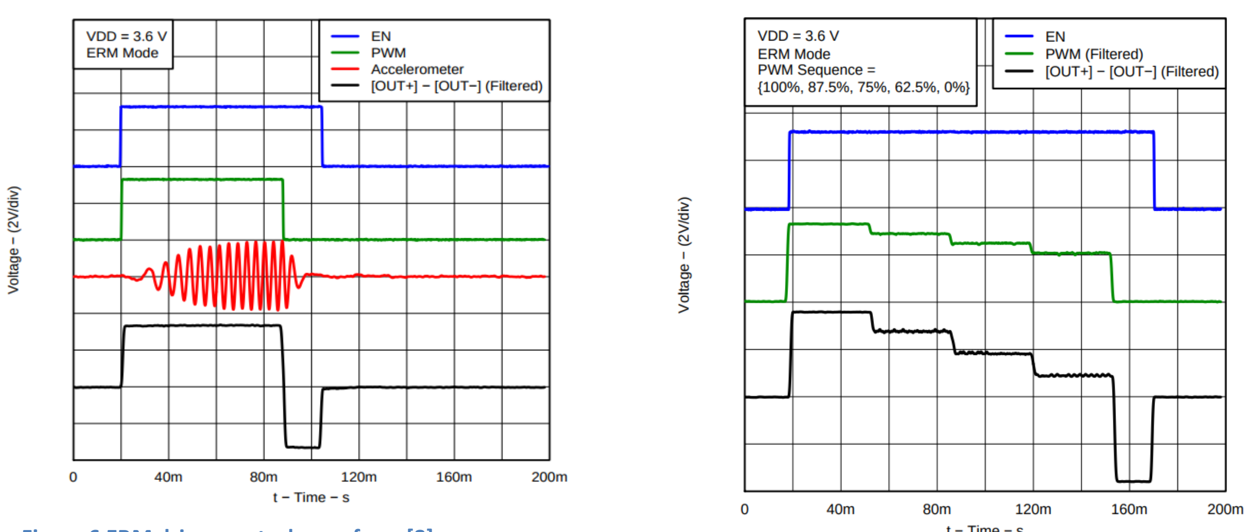


Figure 6 ERM driver control waveform [8]

Each controller takes a PWM signal in and outputs a duty cycle to the corresponding ERM. 50% duty cycle corresponds to motor off, 0% to full reverse, and 100% to full forward, as illustrated in the left plot of Figure 6. The right plot of Figure 6 shows how active braking is handled by the controller IC. Once the PWM duty cycle reaches 50% (corresponding to a stopped ERM), the polarity of the ERM drive voltage is momentarily reversed. This serves to quickly stop the ERM, causing a more abrupt and precise haptic transition.

1.5.3.1 Interface:

Inputs: 3.3V 97 kHz PWM signal (with duty cycle encoding direction and intensity), power supply directly from battery

Outputs: Analog signal to directly drive an ERM.

1.5.4 Mini ERM Actuators

The 8 ERM actuators (commonly called rumble motors) are responsible for generating haptic feedback to the user. They will be affixed to the haptic belt worn about the user's midsection.

1.5.4.1 Interface:

Inputs: Digital signal from 8-channel PWM driver

Outputs: None

1.6 Control Module

The control module is responsible from reading all data from the sensor and power modules, and sending the appropriate commands to the haptic module. It consists of a ARM Cortex-M4 processor with the following interfaces:

- I2C interface to control the haptic module and read the magnetometer
- 4 ADC channels with 10-bit resolution
    - Ambient Temperature (thermistor)
    - Battery Temperature (thermistor)
    - Haptic Intensity Adjustment Potentiometer
    - Battery Voltage
- 9 GPIO Pins
    - 2 for the mode switches (Proximity ON/OFF, and direction ON/OFF)
    - 3 for ultrasound multiplexers select
    - 2 for ping and echo from ultrasonic sensor multiplexers
    - 2 for battery charger status

1.6.1 Feedback Modes

The control module will provide three modes of haptic feedback, which may be superposed:

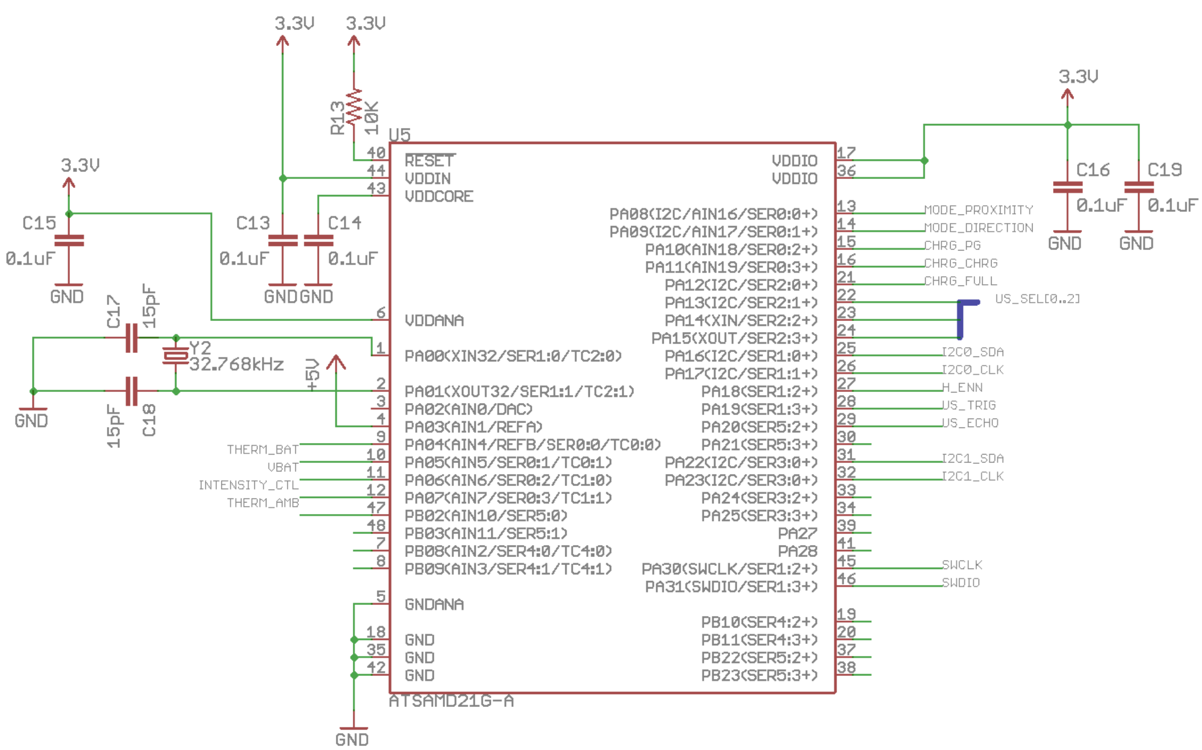
1. Continuous localized -- each motor is intensity independent and continuous in time. Used in proximity mode to report the distance to an object in a given direction

2. Pulsed localized -- Only one or two motors active, pulsing on or off at an arbitrary rate. This is used in cardinal mode to report which direction is north. Two motors may be active when the direction north falls between two ERM's
3. Pulsed global -- All motors pulse on and off at the same arbitrary rate and pattern. This mode is used to communicate the following system conditions:
    a. Battery is low -- 1 pulse every 4 seconds
    b. System is charging -- 1 pulse every second
    c. System is fully charged -- 2 pulses every second
    d. System is shutting down due to battery overheating -- 1 long 1 second pulse

1.6.2 Software Flow Charts

An ARM Cortex-M4 will be used as the microcontroller for this project. It consists of an application processor and board, as well as the software to convert sensor data into haptic responses. The mode switch on the control panel will tell the control module whether it should provide feedback for obstacle detection, cardinal direction, or both. The control module will read the intensity adjustment knob on the control panel and adjust the haptic commands sent to the haptic module accordingly. The flow chart of the program is shown in Figure 8, and the schematic is shown in Figure 7.

Figure 7 Schematic for the control module



The application processor will control the rangefinders through a multiplexer/demultiplexer pair using its GPIO pins. In order to get accurate time-of-flight measurements, interruptible timers integrated into the application processor will be used. The program flow charts are shown in Figure 8, and the microcontroller schematic is shown in Figure 7.

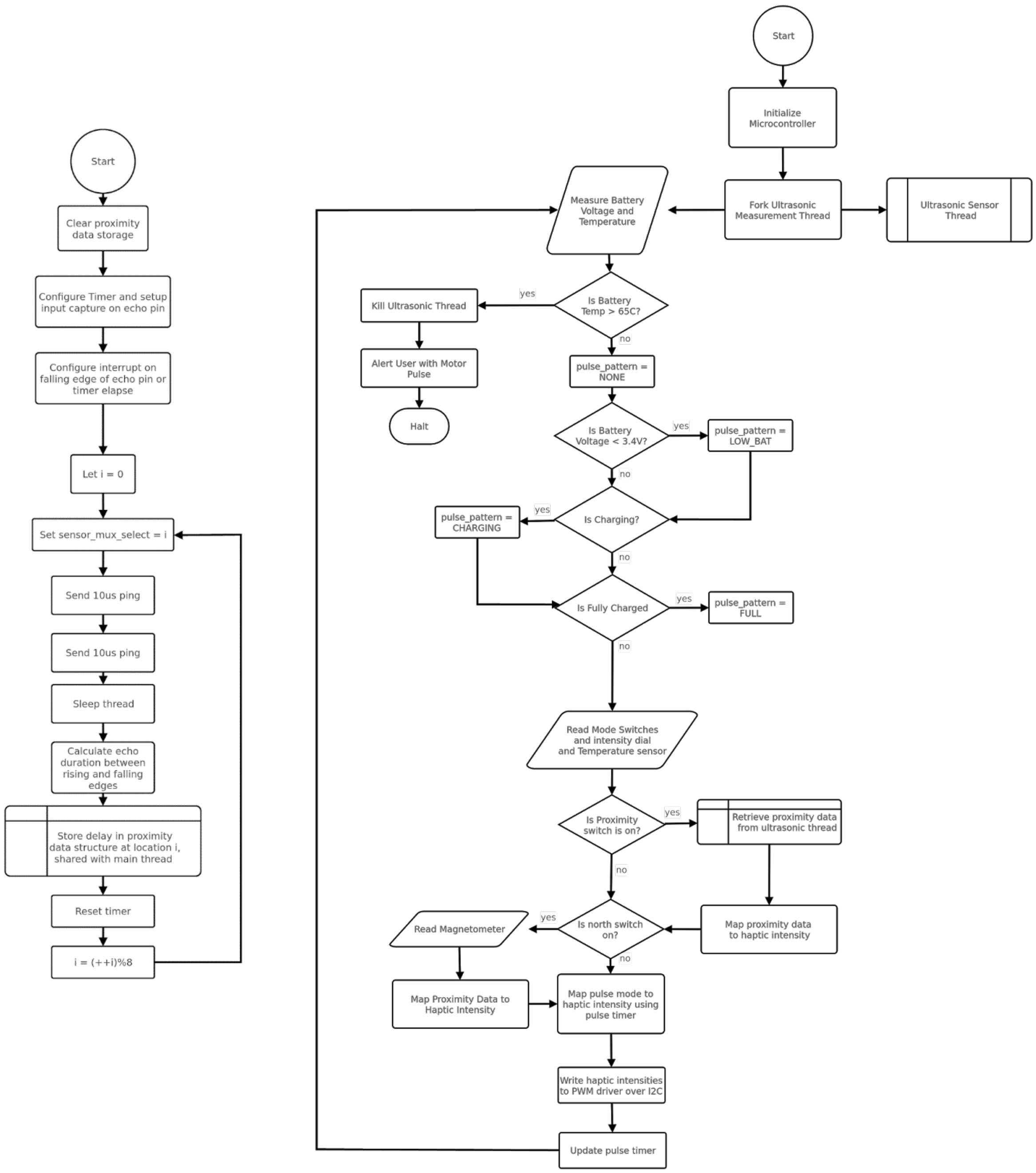


Figure 8 Software flow charts for the Control Module program

1.7 Power Module

The power module provides the Lithium-ion battery for the wearable device and delivers the necessary operating voltages for other modules. It also mitigates the power hazards with regards to user safety with a hazard detection unit, specifically for thermal protection and under-voltage lockout. Finally, it uses a charging IC for the rechargeable Li-ion cell.

In addition, the user must be alerted through the haptic module if the device is in danger of shutting down to prevent hazards, since it will risk leaving the user without mobility aid. Therefore, the power module also outputs data about the current temperature of the battery to the application processor through an analog signal. Finally, the application processor also tracks the voltage of the battery to alert the user about low-power state.

1.7.1 Interface:

Inputs: None
Outputs: 5V power supply, 3.3V power supply, VBATP analog signal to the application processor, VTHERM analog signal to the application processor

1.7.2 Voltage Regulator Unit

The voltage regulator unit will deliver low-voltage DC power to the rest of the modules. The two required operating voltages are 3.3V and 5V, and our chosen Li-ion cell has a nominal voltage of 3.7V: therefore, we need to both step down and step up the battery voltage. To step down the voltage to 3.3V, we will use the LM3671 DC-DC step down converter; to boost the voltage to the 5V range, we will use the TPS61032 boost converter. The regulator circuits are shown below in Figure 9. Both components exhibit efficiency of greater than 90% power conversion and therefore mitigate power loss, an important quality for a wearable device.

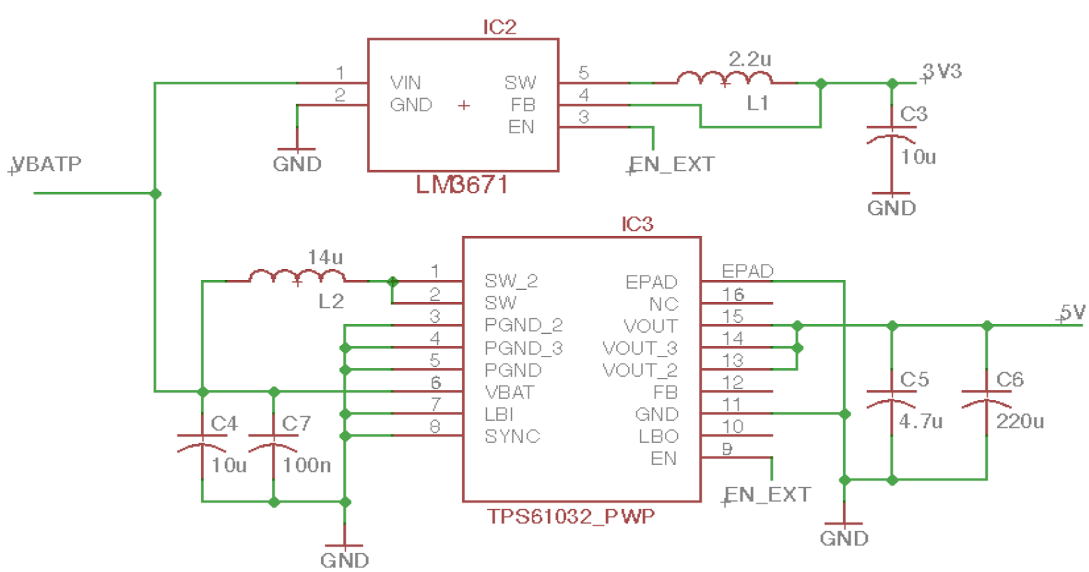


Figure 9 Schematic for the voltage regulator unit

Additionally, the voltage regulators must be disabled if the battery condition becomes hazardous during usage to protect the user. The 3V regulator's enable pin is thus connected to EN_EXT, the digital output from the hazard detection unit which will be asserted high only if the current battery state is non-hazardous, and de-asserted otherwise. Since the 5V regulator also powers the hazard detection unit, it must always be on; instead we implement a pair of MOS elements on the output of the 5V regulator to cut off the power to the rest of the device. PMOS is the element that lets the current through to the rest of the device; the gate of that is driven by an NMOS, whose gate is in turn driven by the EN_EXT signal. Thus, when EN_EXT is high, current is allowed through the PMOS; when EN_EXT is low, current is no longer allowed through.

1.7.2.1 Interface:

Inputs: Input voltage from Li-ion battery, digital signal from hazard detection unit

Outputs: 3.3V and 5V voltage rails

1.7.3 Hazard Detection Unit

The hazard detection unit monitors for hazardous battery conditions that may manifest during normal usage. In such conditions, it will de-assert the EN signal to the voltage regulator unit to isolate the power module from the rest of the system. The battery is in a hazardous state if one or both of the following hazard conditions are true: if the battery is thermally unsafe, or if the battery's voltage is too low. Both conditions impact user safety and battery longevity. The hazard detection unit schematic is depicted in Figure 10.

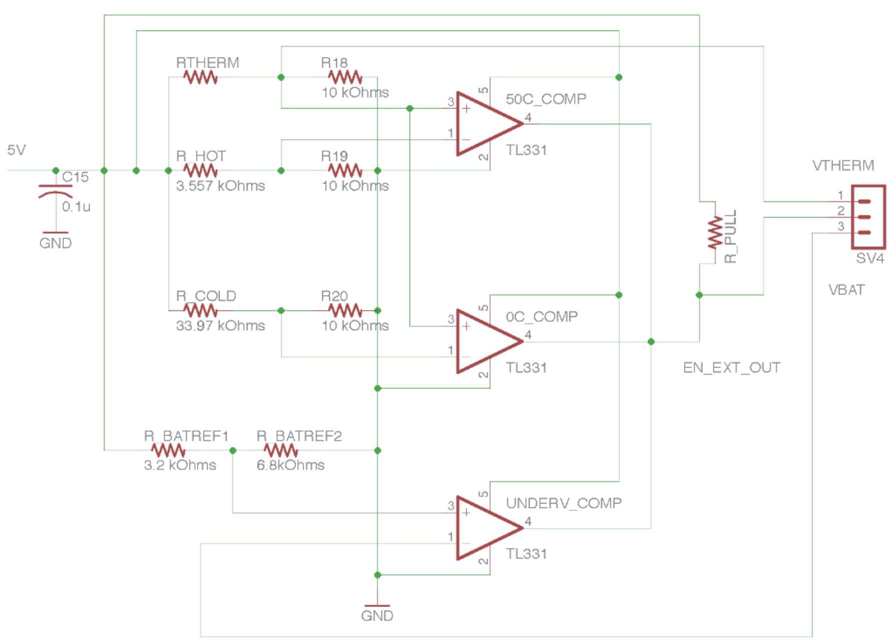


Figure 10 Schematic for the hazard detection unit

The Li-ion battery is hazardous if its temperature exceeds the range of 0 to 50 degrees Celsius. To monitor this temperature, we thermally glue a negative temperature coefficient (NTC) thermistor to the Li-ion battery: our chosen thermistor (NTCLE213) will have an impedance of 33.97 $k\Omega$ at 0 degrees Celsius and 3.557 $k\Omega$ at 50 degrees Celsius. The variable voltage input to the comparators is therefore the voltage drop across R1 (V_{therm}), which will scale proportionally with the thermistor's changing impedance. We provide reference voltages for the 50 degrees C and 0 degrees C boundaries as the other comparator inputs respectively. We choose the following resistor values:
R_{hot}= 3.557 $k\Omega$, R_{cold} = 33.97 $k\Omega$, and R1 = R2 = R3 = 10 $k\Omega$.

The third comparator monitors for under-voltage; it uses the Li-ion battery's voltage as the variable voltage and the 5V voltage source as the reference voltage. The Li-ion battery that we chose (ICR18650) has a nominal voltage of 3.7V, and a discharge voltage of 3.0V. Since the discharge voltage is when the

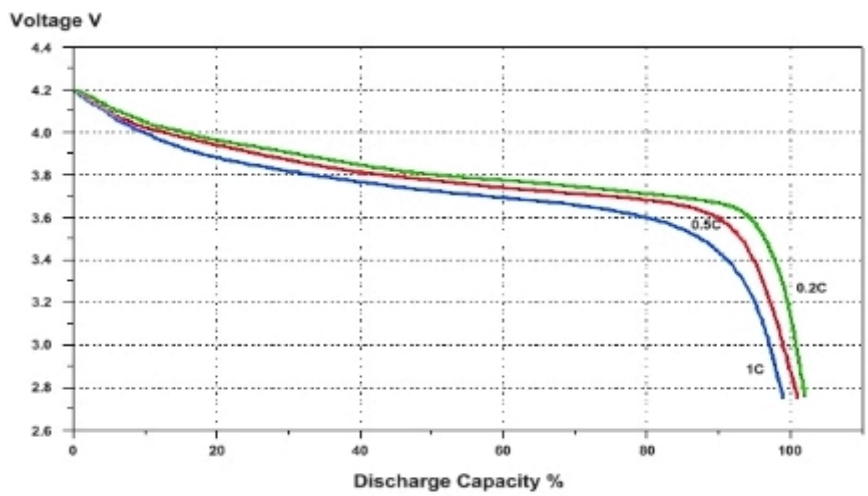


Figure 11 Lithium Ion battery voltage-capacity curves [10]

battery is fully depleted and any further depletion will risk potential hazard, we choose 3.33 as our cut-off voltage. Moreover, Li-ion batteries remain at >3.4V for >90% of their discharge, according to Figure 11, and therefore the under-utilization of our battery is non-significant. In addition, allowing the Li-ion battery to have voltage < 3.3V will cause our 3.3V voltage rail to sag, an undesirable outcome that this comparison also mitigates.

The outputs of the three comparators are joined with a pull-up resistor that connects to the 3.3V voltage source. Since the TL331 comparator has an open collector output, if one or more comparators are active, they will sink current and the combined output will be pulled to ground. This combined output is the EN_EXT signal that is delivered to the enable pins of the voltage regulators. Since the voltage regulators are in shutdown mode if EN < 0.4V and in normal operating mode if EN > 1V, and our EN_EXT signal will output GND if one or more comparator matches and 5V otherwise, this design satisfies the requirements.

V_{therm} is also delivered as the analog signal to the application processor, which will allow the application processor to alert the user if battery is overheating or nearing depletion.

Interface:
Inputs: Input voltage from Li-ion battery
Outputs: Digital EN_EXT signal to the voltage regulator unit, V_{therm}analog signal to the application processor

1.7.4 Charging controller

Charging the Li-ion battery is another area that poses significant safety concerns. Since we are increasing voltage of the battery cell, we must ensure that the battery cell will not exceed the maximum safe voltage of 4.2V, and that charging will not cause overheating of the battery cell.

- **Correct charging algorithm:** Charge at constant current (0.2C to 0.7C depending on the manufacturer of the battery) until the battery reaches 4.2Vpc (volts per cell); then hold the voltage at 4.2V until the charge current has dropped to 10% of the initial charge rate, at which

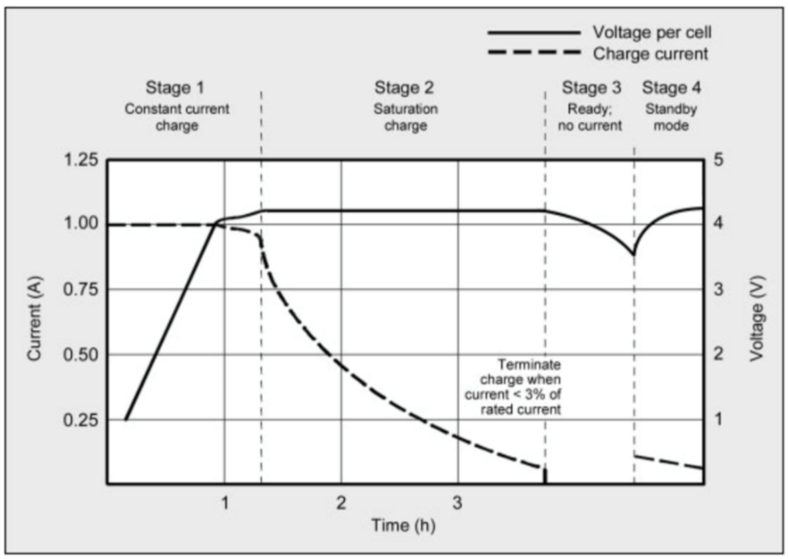


Figure 12 Lithium Ion Charging procedure

point terminate charging. Figure 12 shows a plot of the charging procedure.
- **Overcharge protection:** Stop charging when Vpc rises above 4.2V.
- **Reverse discharge protection:** Prevent charging when charging supply polarity is reversed.
- **Thermal regulation:** Stop charging if battery temperature is lower than 0 degrees Celsius or above 45 degrees Celsius.
- **Overcurrent protection:** Charge current must be below 0.7C.

We choose MCP73833/4, a configurable charging IC that has all of the listed features. We select the following configuration for the MCP73833/4 to suit our chosen Li-ion battery, Adafruit's ICR18650:

- **Constant charging current:** 0.5C = 2200mA
- **Constant charging voltage:** 4.2V
- **Cut-off current:** 0.01C = 44mA

Additionally, we elect to use a DC barrel jack to provide external voltage supply to our charging controller. The assembled schematic is as shown in Figure 13:

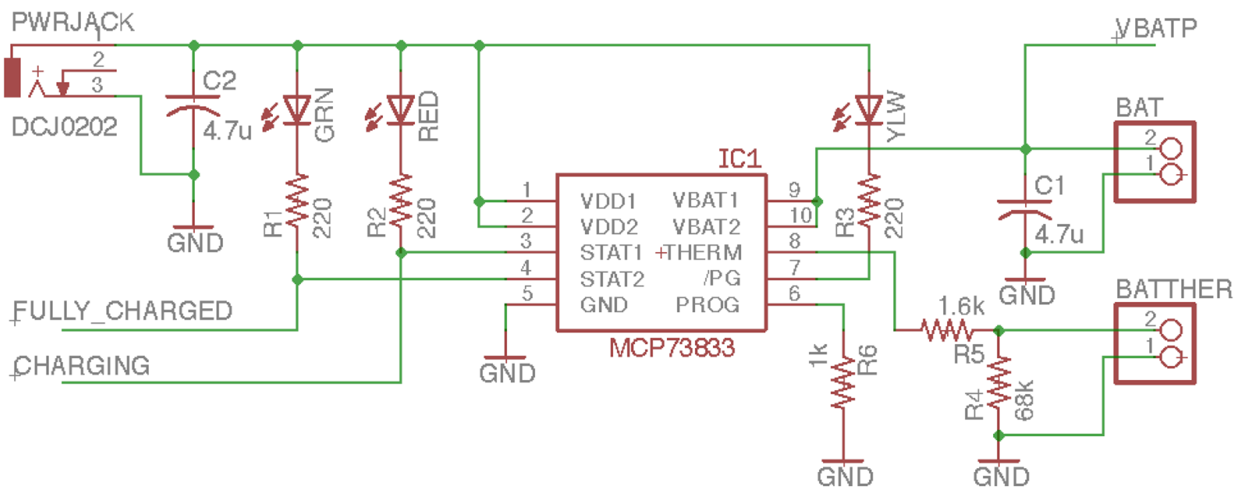


Figure 13 schematic for the battery charger circuit

1.7.4.1 *Interface:*

Inputs: 6V from DC power jack

Outputs: 2200mA charge current to the Li-ion cell

1.7.5 Lithium-ion Battery

We choose to use Lithium-ion battery for our wearable device due to its high density and portability; it is more suitable for wearables compared to other chemical batteries such as lead acid. To determine the size of the Li-ion cell suitable for our device, we use datasheet values to calculate approximately how much power our components draw (using equation 3). The

$$P_{tot} = VI \qquad (3)$$

Component	Quantity	Average Power Consumption/Component
Ultrasonic Rangefinder	8	5V * 15mA = 75 mW
Total Power Consumed by Module	**75 mW (only one sensor is triggered at a time)**	

Table 1 average power consumption per component for the sensor module (Negligible components (μA): temperature sensor, magnetometer, demux, mux, user switches, and potentiometer)

Component	Quantity	Max Power Consumption/Component
ERM Controller and Motor	8	3.6V * 59 mA = 212.4 mW
PWM Driver	1	3.3V * 10 mA = 33 mW

Total Power Consumed by Module	**8(212.4) + 33 = 1732.2 mW**

Table 2 maximum power consumption per component for the haptic module

Component	Quantity	Max Power Consumption/Component
Microprocessor	1	3.3V * 7.3 mA = 24.09 mW
Total Power Consumed by Module	**24.09mW**	

Table 3 maximum power consumption per component for the control module

As for the power module, the voltage regulators are 90%+ efficient and dissipate negligible power, the differential comparators and thermistors draw negligible power, and the charging IC and DC power jack will draw power from an external power supply. Therefore, the power impact of the power module is insignificant.

We find through our analysis that our device consumes an approximate 0.5043Ah. We choose to use Adafruit's ICR18650 Li-ion single cell battery, which is rated at 4.4Ah with standard discharge of 0.2C = 880mA. We will require a discharge rate of 0.115C to accommodate our device, and therefore one ICR18650 will yield 8.7 hours of battery. Thus, one ICR18650 will be able to guarantee our user a full 8 hours of battery capacity for a typical day's use.

Interface:

Inputs: 4.2 charging voltage from charging IC

Outputs: power supply line to the rest of the power modules, VBATP (positive terminal) to analog processor

2 Design Verification

In order to verify the functionality of our design, we developed a requirements and verification (RV) table to define the specification of each component of our design. Our final RV table is shown in Table 7 and includes both the quantitative requirement and a testing procedure. We made sure all verifications passed and have recorded each measurement in Table 7.

2.1 Sensor Verification

In addition to our requirements and verification testing, we ran tests solely on the ultrasonic sensors in order to gain a better understanding of their capabilities and limitations. The first test we ran included sampling ping times many times at a precise distance. The goal of this test was to determine the volatility and inherent error of the sensors. The error rate as well as measurement standard deviation is

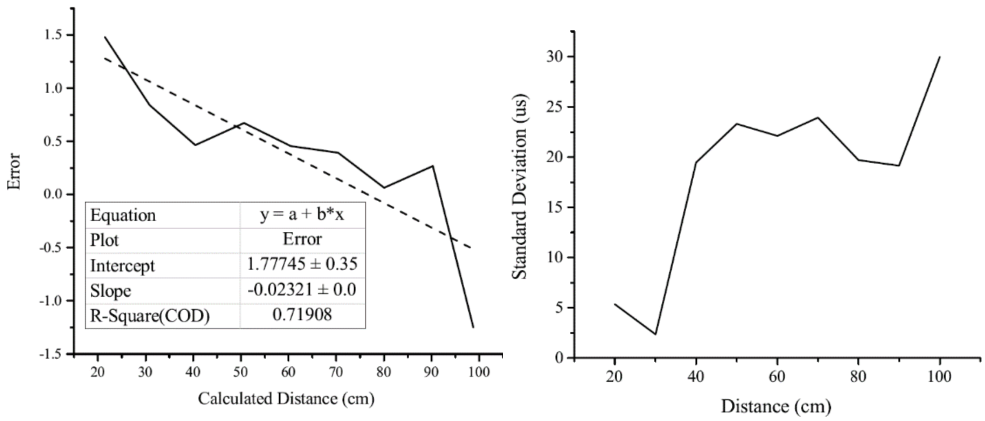


Figure 14 Ultrasonic rangefinder characterization

shown in Figure 14. From this data, we can see that the sensors have a small error rate. Additionally, a significant amount of the error can be calibrated out using a simple two term error model, which can be determined through two measurements.

2.2 Control Module Verification

Because the control module is responsible for processing the data read from the sensors, it is crucial that the algorithms it uses to filter and parse the inputs runs quick enough to generate a haptic response before a user has collided with an obstruction.

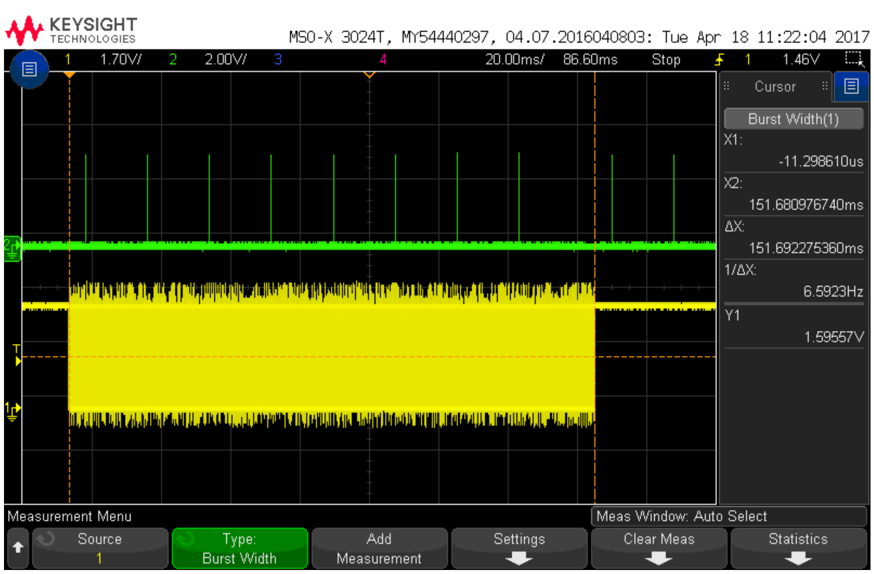


Figure 15: Verification of control module latency

To measure the end-to-end latency from when the first ultrasonic sensor was read to when the corresponding haptic motor was driven, we used an oscilloscope to inspect the control signals. In Figure 15, the yellow trace shows the vibration motor PWM control being shut on and off. The green signal shows the 8 ultrasonic sensors being read. As indicated by the cursors, the latency is 151ms, which is within our requirement of 200ms. Similar verifications were done according to the procedures in the RV table.

2.3 Power Verification

We fully verified each of the four submodules requirements – charging controller, regulators, hazard detection, and Li-ion battery – and describe the verification methods and their results below.

- Charging controller: we verified that the charging current never exceeded 3080 mA throughout charging (it topped out at 660 mA with our charging configuration). We verified that the charging current becomes 0-0.005 mA when the battery temperature goes out of the range of 0-50 degrees Celsius, which we modeled by submerging the thermistor in temperature-controlled waters and monitoring the current flow with an ammeter. Finally, we verified that the charging current becomes 0-0.005 mA when the battery polarities are reversed.
- Regulators: We modeled the load of the rest of the device through approximately 180 kOhms and 330 kOhms respectively for 5V and 3.3V, and ensured the voltages stayed constant.

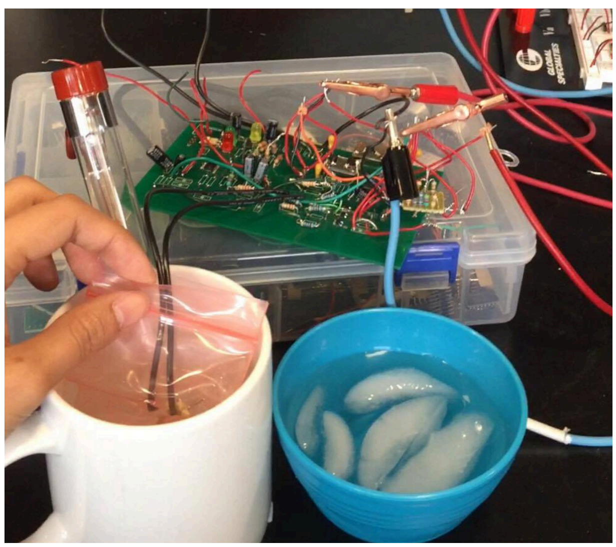


Figure 16: Testing power temperature constraints

- Hazard detection: We verified that the voltage from 3.3V and 5V will both cut out when any of the three hazards manifest. We test this by modeling the battery through a DC power supply, and by submerging the thermistor in temperature-controlled waters.
- Li-ion battery: While we would have preferred to actually run the device for the full 8 hours as our testing method, due to time constraint we instead found the maximum current draw of the device, which was 536 mA when all the ERMs are driven at 100% duty cycle. Our 4.4Ah Li-ion battery is therefore sufficient to drive the device for more than 8.2 hours.

3 Costs

3.1 Parts

Table 4 Component Cost Breakdown

Part	Manufacturer	Quantity	Retail Cost ($)	Bulk Purchase Cost ($)
Ultrasonic Range Finder	SparkFun	8	$3.95	$3.95
Demux	On Semiconductor	1	$0.38	$0.11
Mux	On Semiconductor	1	$0.37	$0.11
Magnetometer	STMicroelectronics	1	$2.12	$0.66
Temperature sensor	Analog Devices	1	$0.86	$0.75
Rocker switch	CW Industries	1	$0.73	$0.46
Rotary potentiometer	TT Electronics/BI	1	$1.29	$0.58
PWM Driver		1	$2.31	$1.14
ERM Driver	Texas Instruments	8	$1.92	$0.94
Dual 2-input NOR	On Semiconductor	2	$0.44	$0.14
5 pack 3V ERM motor	Amazon	2	$4.80	$4.80
2x8 0.1in pin header	Harwin	1	$0.79	$0.33
3.3V Regulator	Texas Instruments	1	$0.92	$0.53
5V Regulator	Texas Instruments	1	$2.83	$1.49
Differential Comparators	Texas Instruments	3	$0.58	$0.25
Thermistor	Vishay	1	$0.76	$0.26
Linear Charger	Microchip	1	$0.88	$0.67
DC Power Jack	Conec	1	$0.73	$0.36
Adafruit 4.4Ah Li-ion	Adafruit	1	$19.95	$19.95
ATSAMD21G18A-AUT	Microchip	1	$3.22	$2.66
Total			$97.32	$79.81

Table 5: Component costs

3.2 Labor

Table 6 Labor Costs

Name	Project Role	Hours Worked	Hourly Rate	Total Cost * 2.5 Correction Factor
Adam Auten	Electrical Engineer	240	$30	$18,000
Yuan Chih Wu	Electrical Engineer	240	$30	$18,000
Robert Kummerer	Electrical Engineer	240	$30	$18,000
		Total Labor Cost		**$54,000**

4 Conclusion

4.1 Accomplishments

Our finished vest met all the requirements we had previously set. It is able to translate object distance to haptic vibrations, administer a vibration in the north direction, and additionally deliver user information through haptic encoding, such as charging indication and battery low indications. It was independently powered through the power module, which has hazard detection integrated in its design, and is thus a complete wearable.

4.2 Ethical considerations

Our product is meant to be a supplementary aid to the visually impaired. It is our ethical obligation to ensure to the best of our ability that this product will bring no harm to its users. The IEEE Code of Ethics Code 3 claims that we must be honest and give realistic claims about the capabilities of our device [9]. In order to prevent accidents and to be in accordance with the IEEE Code of Ethics, we must make it clear that this product, at this stage, is by no means a replacement for a white cane. Additionally, there are components of our design that can be physically dangerous to the user, namely the battery pack. According to IEEE Code 1, we must accept responsibility for the safety of the users of this device, and we must make clear any factors that may be dangerous [5]. In order to properly protect the user from potential malfunctions of the battery pack, we ensure that it has Ingress Protection (IP) 63 [6]. According to the General Battery Safety guideline [7] from the ECE 445 course page, only battery voltages in the 3.0-4.4V range must be allowed. In the event of an extreme voltage, our device cuts off the battery, after warning the user about the imminent power shutdown through the haptic feedback.

4.3 Future work

While this project met our requirements and could be considered a success, it did not solve the problem as well as we had hoped. To fulfill our initial objective, further work is needed. One of the first improvements we would make would be to replace the current ultrasonic sensors with a superior sensor. This could either be another ultrasonic sensor, a LIDAR sensor, or a camera. Each of these options comes with their own unique challenges such as price, computational requirements, range, and size. Another avenue we could take to improve our design is to improve the brains behind it. In the future, we could implement cleverer algorithms for filtering the data from the ultrasonic sensors. Additionally, increased sampling rate could cut down on numerous problems such as filtering time and end-to-end latency.

5 References

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6 Appendix A Requirement and Verification Table

Table 7: System Requirements and Verifications

Requirement	Verification	Verification Status
Sensor Module		
Ultrasonic Sensors		
Ultrasonic sensors must be accurate to within 20cm	1. Setup ultrasonic sensor 20cm from a wall 2. Record distance calculated 3. Repeat measurement every 20cm until 2m is reached. 4. Verify all measurements are within 20cm of true distance. 6.1.1	Pass
Ultrasonic sensors must have an effective range of 2m	1. Place ultrasonic sensor 150cm from a wall. 2. Record distance calculated 3. Move sensor away from the wall by 10cm and record distance calculated again 4. Repeat step 3 until 2m has been reached. 5. Verify that at 2m distance, the calculated distance is accurate and upholds Requirement 1.	Pass Under ideal conditions
Temperature Sensor		
Must be able to sense from -10°C to 30°C with a 5°C accuracy.	1. Find three areas of known temperature (inside, outside, refrigerator) 2. Take 10 temperature measurements in each location separated by 1 minute 3. Ensure temperature has stabilized (device has reached ambient temperature) 4. Verify stabilized temperature within 5 degrees of true temperature	Pass Calibration was needed
Magnetometer		
Must be able to sense geomagnetic north within a 22.5° accuracy.	1. Determine geomagnetic north using a compass or other tool 2. Record north direction given by magnetometer	Pass Calibration was needed

	3. Rotate device 22.5 degrees and remeasure 4. Verify all recorded measurements are within 22.5 degrees geomagnetic north	
Haptic Module		
Each ERM must not draw more than 150 mA when supplied with 3.3V	1. Using a lab power supply apply 3.3V to the motor. 2. Verify that the lab supply is sourcing less than 150mA	Pass 85 mA
ERM must be able to support both continuous operation and pulsed operation of 10% duty cycle at 2 Hz. These two modes must be able to be distinguished by their haptic response.	1. Apply a 10% duty cycle 3.3V PWM signal at 2Hz with a signal generator. 2. Allow a blindfolded person feels the response. 3. Apply a continuous 3.3V signal to the ERM. 4. The test subject should be able to differentiate between pulsed and continuous modes.	Pass
PWM Driver must be able to update all 8 channels' duty cycles at least once every 200 ms.	1. Create a test program to alternately turn all PWM motors full on and full off. 2. Flash the program to the device 3. With an oscilloscope, measure the voltage across the ERM with time. 4. The test passes if the delay between changes for a given motor is < 200ms.	Pass
Control Module		
When board is powered on a full battery with both proximity and directional feedback off, no motors should be running.	1. Fully charge the battery 2. Turn off the proximity and direction feedback switches on the control panel. 3. Monitor the I2C bus output to the haptic module with a logical analyzer. 4. Verify all data bytes are 0x80, corresponding to 50% duty cycle (motors off).	Pass

The end to end latency between a proximity sensor being read to a motor turning on needs to be less than 200ms.	1. Fully charge the battery 2. Attach a single proximity sensor. 3. Monitor both the echo pin and the I2C bus on the logic analyzer. 4. Set the scope trigger on the falling edge of the echo pin, and set the timespan to be > 250ms 5. Trigger the sensor with a large flat object, and record the delay until the haptic command is send on the I2C bus.	Pass 151 ms
The processor must refresh the duty cycle of all 8 PWM channels at least once every 200 ms.	1. Fully charge the battery 2. Attach logic analyzer to the I2C bus between haptic and control module. 3. Turn on device, and measure the delay between writes of the 4. I2C address If this delay is < 200ms, the test passes.	Pass 173 ms
When an object is placed less than 20cm of a sensor, the ERM corresponding to that sensor must be turned off.	1. Fully charge the battery 2. Attach logic analyzer to the I2C bus between the haptic and control module 3. Turn on the device. 4. Place obstruction between 30cm and 100cm in front of ultrasonic range sensor 5. Verify that the data byte sent to the PWM controller is > 0x80 6. Move obstruction to within 20cm of the sensor. 7. Verify that the data byte sent to the PWM controller is 0x80	Pass
Power Module		
Voltage Regulator		
Handle input voltage range of 3.3V-4.2V from the battery, and output stable voltage rails of 3.3V @ 18 mA and 5V @ 15 mA	1. Set the voltage supply to 3.3V and connect the voltage supply to the input of the regulator unit 2. Attach a 184 k Ω resistor as the load of the 3.3V rail, and a 334 k Ω resistor as the load of the 5V rail 3. Verify with a voltmeter that the voltage drop across the 184 k Ω resistor is 3.0-3.6V, and that the	Pass 3.31 V 5.04 V

	voltage drop across the 334 k Ω resistor is 4.7-5.3V 4. Repeat step 2 and 3 for every 0.1V increment of the voltage supply until 4.2V is reached	
Safety		
Stop battery discharge if battery temperature exceeds 50 ºC	1. Put the battery in a fireproof bag 2. Attach a 184 k Ω resistor as the load of the 3.3V rail, and a 334 k Ω resistor as the load of the 5V rail 3. Bring an oven to 51 ºC and place the bag inside 4. Wait 3-5 minutes until the battery reaches 51 ºC 5. Verify with a voltmeter that the voltage drop across both resistors are approximately 0V-0.005V.	Pass Battery discharge current drops to μA
Stop battery discharge if battery temperature drops below 0ºC	1. Put the battery in a fireproof bag 2. Attach a 184 k Ω resistor as the load of the 3.3V rail, and a 334 k Ω resistor as the load of the 5V rail 3. Put the bag in a bucket of water and ice 4. Wait 3-5 minutes until the battery reaches 0ºC 5. Verify with a voltmeter that the voltage drop across both resistors are 0V-0.005V.	Pass Battery discharge current drops to μA
Stop battery discharge if battery voltage falls below 3.3 volts per cell	1. Let the battery deplete to around 3.4 volts per cell 2. Attach a 184 k Ω resistor as the load of the 3.3V rail, and a 334 k Ω resistor as the load of the 5V rail 3. Connect a voltmeter across the cell 4. Verify that the voltage drop across both resistors are 0V-0.005V when the battery voltage < 3.3V 5. Leave the apparatus alone for at least an hour 6. Verify that the battery voltmeter still displays 3.3V	Pass Battery discharge current drops to μA
Charging		

Deliver charge current of 0mA when Vpc rises above 4.2V or if charge current becomes ~0.1C = 44mA	1. Let the battery cell deplete to < 4.0V 2. Connect a voltmeter across the battery cell 3. Connect the charging IC's power jack to a 6V power supply 4. Probe the charging IC output with an ammeter, and verify that charging current becomes 0-0.05 mA if either Vpc > 4.2V or if charge current is within the range of 35 mA to 50 mA	Pass Charge current drops to μA
Must deliver charge current of 0mA when charging supply polarity is reversed	1. Let the battery cell deplete to < 3.5V 2. Reverse the connection of the lead lines of the battery on the charging IC 3. Connect the charging IC's power jack to 6V power supply 5. Probe the charging IC output with an ammeter, and verify that charging current is 0-0.05 mA	Pass Charge current drops to μA
Must deliver charge current of 0mA if battery temperature is above 45 ºC	1. Let the battery cell deplete to < 3.5 V 2. Put the battery in a fireproof bag 3. Connect the charging IC's power jack to a 6V power supply 4. Bring an oven to 51 ºC and place the bag inside 5. Wait 3-5 minutes until the battery reaches 51 ºC 6. Verify with an ammeter that the current output of the charging IC is 0-0.05 mA.	Pass Charge current drops to μA
Must deliver charge current of 0mA if battery temperature is lower than 0 ºC	1. Let the battery cell deplete to < 3.5V 2. Put the battery in a fireproof bag 3. Connect the charging IC's power jack to a 6V power supply 4. Put the bag in a bucket of water and ice 5. Wait 3-5 minutes until the battery reaches 0ºC	Pass Charge current drops to μA

	6. Verify with an ammeter that the current output of the charging IC is 0-0.05 mA.	
Must deliver charge current of at most 0.7C = 3080mA at all times	1. Let the battery cell deplete to ~3.3V 2. Connect the charging IC's power jack to a 6V power supply 3. Record the charge current output of the charging IC until charging terminates 4. Verify that charge current never exceeded 3080mA-3200mA	Pass Charge current maximum of 650 mA
Battery		
Battery pack must last at least 8 hours for all the components on the device	1. Charge the battery pack until charging terminates 2. Connect battery to rest of the device 3. Leave it running with a rotating apparatus, such that the device is continuously drawing power to reflect normal usage 4. Leave it running for 8 hours 5. Use the device to verify it is fully functional after 8 hours	Pass Battery life extrapolated to be 8.2 hours based on 536 mA max current draw