SEEING-EYE HAT

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Abstract

This report describes the implementation of a Seeing-Eye Hat. It is designed to aid those with visual challenges in understanding their surroundings, using haptic feedback to inform users of obstacles in a 360-degree range. The project's keystone is a LiDAR-Lite v1 sensor that works with a Doppler RADAR to provide both a general understanding of the surroundings and emergency collision detection from the front. Based on the data obtained by the sensors, the corresponding haptic motors will be powered on to indicate the presence of objects in their direction.

The final project was ultimately successful. Each high-level requirement determined at the start of the project was fulfilled. The document will begin with an overview of the project goals, move into the design process, and conclude with ethical considerations and important takeaways from the experience.

Contents

1. Introduction

1.1 Problem and Solution

Visual impairments cause individuals to encounter challenges in independently navigating their surroundings, which results in lowered spatial awareness and concern with personal safety. One solution on the market is the use of canes, but there is an issue with their limited range.

An alternative solution to this problem is a hat designed to empower blind individuals by providing them with a 360-degree field of view. It utilizes a LiDAR-Lite v1 sensor to assist navigation by providing accurate distance measurements in all directions, and a Doppler RADAR for emergency collision detection directly in front of the user. This technology converts the surrounding environment into up-to-date spatial information that enables greater freedom and independence in navigation. The hat also includes vibration motors placed within the hat to indicate the presence and direction of nearby objects, intended to assist the user with making decisions through the navigation process.

1.2 Block Diagram Overview

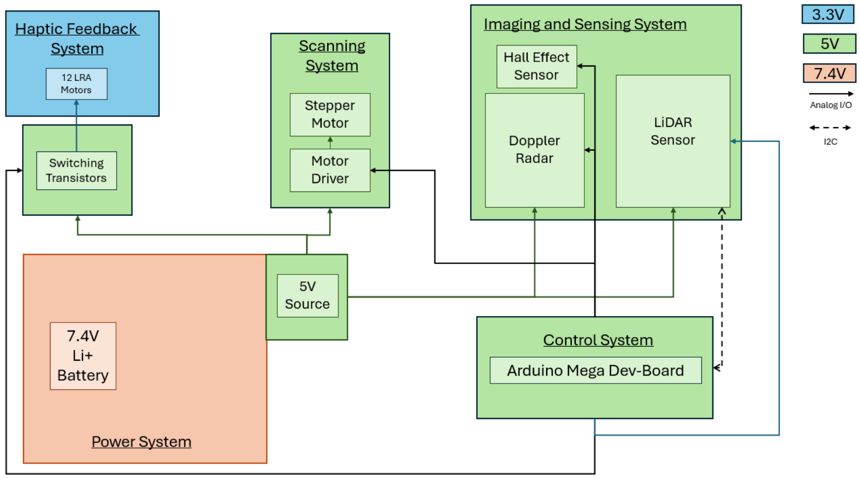


Figure 1: Block Diagram

The control system is the computational core of the project. It integrates and sends data between each other system. The Imaging and Sensing system provides LiDAR and Doppler information to the control unit. The Scanning System rotates the LiDAR, giving the control unit a 360-degree range of measurements. The haptic feedback system is the primary output of the project. It consists of 12 haptic vibrational motors.

Since the start of the project, the block diagram has been simplified. Notably, the PCB Control system was replaced with an Arduino development board. The power system was simplified to a single commercial battery. To narrow the scope of the project, the accelerometer was removed from the imaging and sensing system and VGA compatibility was removed.

1.3 High Level Requirements

The hat was created to meet the following requirements listed below.

1. It should be able to image a room with a similar structure to ECEB 2072 at least 0.5 meters from the center, and its behavior should be viewable by others through a monitor. It must also have a 360-degree range with an angular resolution and accuracy of up to 25 degrees and use haptic feedback in its functionality.
2. It can detect objects approaching the user from front, back, below, and both sides within 2 seconds.
3. Navigational Success: The hat must detect and produce stimuli to inform the wearer of a wall that is up to 5 feet away from them in all directions.

2. Design Procedure

2.1 Control Unit

The control unit is responsible for bringing all the other subsystems together to deliver a product that can inform the user of nearby obstacles within a 360-degree range within a reasonable time. It uses readings from the LiDAR and Doppler sensors to activate the correct motors in the Haptic Feedback system. Several metrics were used to select a microcontroller for the PCB. First, we needed at least 13 analog pins: 12 for the haptic motors and 1 for the Doppler RADAR. Second, we required compatibility with the Inter-Integrated Circuit Protocol (I2C), to enable interfacing with the LiDAR and obtaining the distances critical to identifying the nearest obstacle in its current direction. Finally, our original design required at least 12 digital pins to interface with the array of hall-effect sensors.

After looking into the ones stocked by the department, we decided on the STM32F401 microcontroller. It was programmed via the SWD debug header in conjunction with the development STM32 board that could be checked out. However, we ran into several issues with programming the microcontroller. It was difficult to solder it to the PCB correctly due to the small size of the pins. Once it was on, there were problems with getting code to work on it. Ultimately, we switched to an Arduino Mega to handle all the pins the project required, which vastly simplified programming [1]. The functions of the control unit were also modified based on the switch, due to a newfound ability to simplify the other subsystems. This will be elaborated on further in the details section of this report.

2.2 Sensing System Design

2.3.1 LiDAR

The LiDAR is the most critical component in our system. It is responsible for gathering the distance measurements in all directions that the project requires to activate the corresponding haptic motors. and provide the user with an accurate understanding of the layout of their surroundings. To determine the distance to a forward-facing obstacle, the LiDAR uses a measurement technology called ‘time of flight’. It transmits an optical signal to the obstacle, waits until it is reflected back, and uses the time delay between these two steps to calculate the distance [2].

2.3.2 Doppler

The Doppler RADAR is another sensor that we used to determine proximity to objects but was relegated to emergency collision detection. It operates by amplifying a received signal and converting it to a square wave that could be read as either a digital 0 or 1 [3]. As the RADAR goes low during the presence of an obstacle, the control unit detects this signal and activates the haptic motor in front.

2.3.3 Hall-Effect Module

The Hall-Effect module tracks the position of the LiDAR. Hall-Effect sensors are widely used non-contact proximity sensors and redirect current based on the position of an external magnetic field [4]. A magnet is mounted to the scanning mechanism to trigger the Hall-Effect module. The Hall-Effect module works closely with the control unit to track the position of the scanning mechanism.

The first design for the Hall-Effect module utilized only one sensor [5]. The plan was to use the Hall-Effect sensor pin as a hardware interrupt to the control unit, and the control unit would use a known RPM of the motor to keep a constant cycle of knowing where the motor should be. This would be resynchronized each revolution by the Hall-Effect sensor. This idea was deemed too complicated on the software end.

The next concept was to use one Hall-Effect sensor for each haptic motor. This design would use interrupt handlers to tell the control unit exactly when the LiDAR reached any relevant position. Whenever the scanning mechanism would reach any point of interest, the control unit would be told to run a routine to take a LiDAR Read and process it as haptic feedback.

This design proved to be mechanically difficult. The circuitry took up a lot of physical space, and small hardware inconsistencies made the system unreliable. During testing, we found one of the Hall-Effect circuits would malfunction at a time, but which one was inconsistent. This led us to search for alternatives.

The switch to a stepper motor in the scanning mechanism allowed us to revert the module down to a single Hall-Effect sensor. This was possible since we now had the capacity to use a stepper motor to control the LiDAR's motion, and the Hall-Effect module now serves the purpose of calibrating the LiDAR to start at the front of the hat before its main operation. Once the Hall-Effect sensor goes low, the sensor is facing forward and can now start on reading distances in the 12 directions that we set up.

2.3 Haptic Feedback System Design

The Haptic Feedback system's purpose is to translate the locational data into sensory feedback for the user. The core design has remained consistent. Haptic Motors, otherwise known as Linear Resonant Actuator (LRA) Motors, are used to convey sensor feedback to the user. The system consists of 12 haptic motors, and 12 switching transistors [6].

Haptic motors are evenly distributed across the inside rim of the hat. This divides the surrounding area into evenly spaced "zones" extending out from the angles between the motors. For example, the final product uses 12 motors. This places a motor every 30 degrees around the hat. Each haptic motor now represents a 30 degree "slice" of the world surrounding the user.

The strength of the vibration is determined by the Control Unit. The control unit uses a PWM Signal and switching transistors to regulate the power delivered to the motor. These are used to not over-tax the maximum current drawn from the microcontroller. With a sufficiently powerful microcontroller, and a limit on the maximum number of motors activated, the switching transistors may be able to be removed.

We used a 150 cm threshold distance to turn on the motor. We considered having the strength of the signal proportional to the distance to the nearest measured object within the motor zone. Testing showed that this was difficult to perceive by users.

The proposed design intends to have all the motors on at one time. When testing, we learned that most test subjects struggled to distinguish the locations of the haptics once more than one was active simultaneously. Therefore, we limited the scope to only pulse one motor at a time. We also considered using 8 motors instead of 12 if the product became overstimulating.

2.4 Scanning System Design

The scanning system's primary purpose is to rotate the LiDAR. It also rotates the magnet used to trigger the Hall-Effect Sensor used by the control unit during the calibration process. The most important requirement of the scanning system is to ensure the LiDAR can spin fast enough to meet the "one measurement update every two seconds" requirement, translating to a 30RPM rotation. The scanning mechanism and the sensing system work to track the position of the motor, and consequently the LiDAR for mapping distance measurements to directions and haptic motors.

2.4.1 Initial Design Iterations

Multiple mechanical designs were considered for the drivetrain of the scanning system. Initially a gear-driven drive train was chosen for simplicity. A rendering of the hat with this proposed design is seen in figure 3 below. However, a gear-driven drive train was unable to have enough clearance for all 12 Hall Effect sensors, so the design was quickly abandoned.

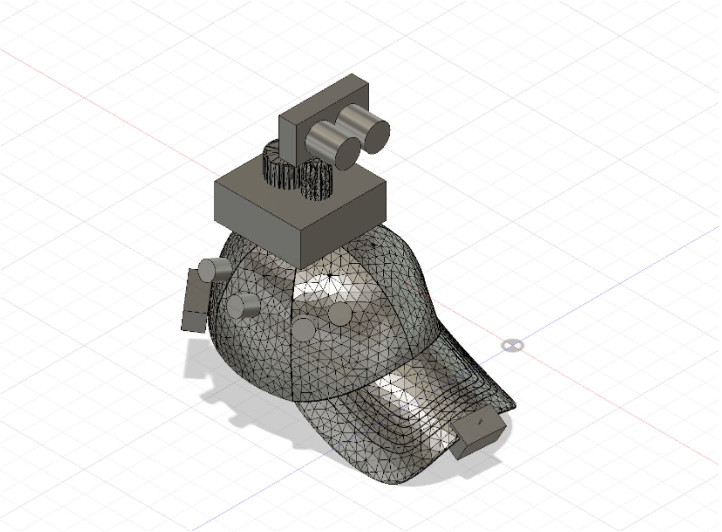


Figure 2: CAD Concept Art

The second iteration was a belt-driven design; however it had issues with being too short and not being able to mount the LiDAR high enough. Another design shown in Figure 4 below shows another iteration of the design with a taller mount for the LiDAR with magnetic mounting for the LiDAR, but it ran into issues with friction while spinning and not enough clearance for the Hall-Effect module.

Figure 3: First model of the scanning mechanism

2.4.2 Final Design

The final iteration of the design centered around a belt-driven design over a gear driven design. This allowed for greater clearance and the need for less precise tolerancing when sizing the Hall-effect Module of the sensing subsystem. Additionally, the design utilized a ball bearing for smooth rotation.

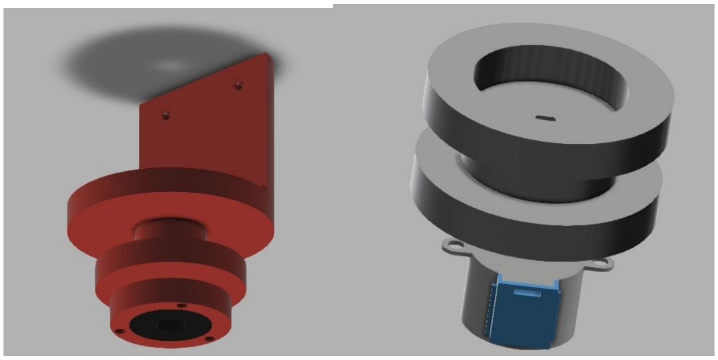


Figure 4: Scanning Mechanism Final Version CAD

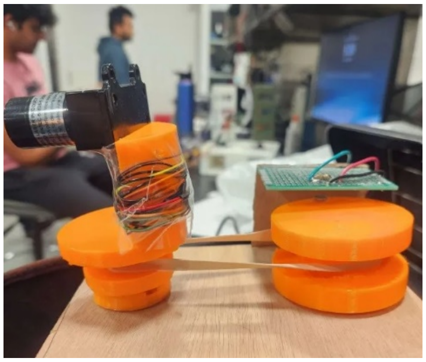


Figure 5: Scanning Mechanism Final Implementation

The LiDAR requires 5 wires for operation and rotation to scan from multiple angles. The existence of these wires necessitates that the LiDAR must be driven by a gear instead of the motor directly. To maintain the structural integrity of the wires and prevent gear impingement, the wires must remain static relative to the LiDAR and gear. Therefore, a slipring was required for this design.

Initially, the scanning mechanism consisted of a brushed DC motor and a 1:1 gear ratio. The benefit of this system is that more LiDAR readings could be collected faster, which would provide a better user experience. However, synchronization with the Hall-Effect module proved difficult to integrate in the mechanism, as it was prone to failures to activate and false positives. This led to difficulties when trying to synchronize readings, as recalibration would be required for each rotation.

The final version of the scanning mechanism uses a stepper motor and a 2:1 gear ratio to turn the LiDAR for the sake of rotational accuracy from calibrating step distance. This reduced some developmental burdens when programming. Detrimentally, the motor operates at 15RPM. We used a 2:1 gear ratio to successfully meet the 30RPM requirement.

2.5 Power System Design

The power system had a dynamic development process. Failures during the verification process, alongside untimely component ordering problems, caused the team to abandon the original power system described in the proposal.

Our team proved resourceful. With two days until the demonstration, we found a commercially available and accessible power system that still passed every verification test that we designed for its predecessor. This section will first describe the final version of the power system as it appeared in the demo. Afterwards, we will detail the process of designing the failed power system.

2.5.1 Final Power System

The final product utilizes a multi-stage power system. The primary power supply is a standard USB Portable Cell Phone Charger. The rated output voltage from the portable charger is 5 V. The rated output current is 2.1 A.

The primary battery directly powers the Control Unit. Alongside acting as the control unit, the Arduino Mega functions as the voltage regulators for the power system. The development board contains linear regulators to create stable 5 V and 3.3 V power buses. These two buses are used to power all components of the Scanning, Sensing and Haptic systems. The maximum current draw from the Arduino is 800 mA. This effectively limits the maximum current draw from the power system to 800 mA. The Arduino development board has built-in Undervoltage Lockout and Short Circuit protection. Under either of these conditions, the Arduino will shut down, which cuts power to all other subsystems by extension.

This model was chosen because our PCB design failed the final verification test. However, this design has a lot of merit. Custom designs introduce points of failure. Utilizing stable commercial components grants consistency to a design, which is valuable for key systems. The new power system was able to pass the required verification tests. Prioritizing time and consistency allowed the product to be completed and for the demo to be successful.

2.5.2 PCB Power System

The power system's design process can be described as a lesson in overengineering. The power system was designed as a part of the standard project PCB. The initial concept was to use a 7.4 V LiPo battery as the primary power supply. The on-board power system would include branches for a 5 V and a 3.3 V power bus. This would be accomplished with two buck converters. Buck converters were used because, at the time, we did not think linear regulators could perform the necessary conversion without overheating. Undervoltage and short circuit protections were initially provided by e-Fuse components. Figure 6 shows the schematic included in the design document.

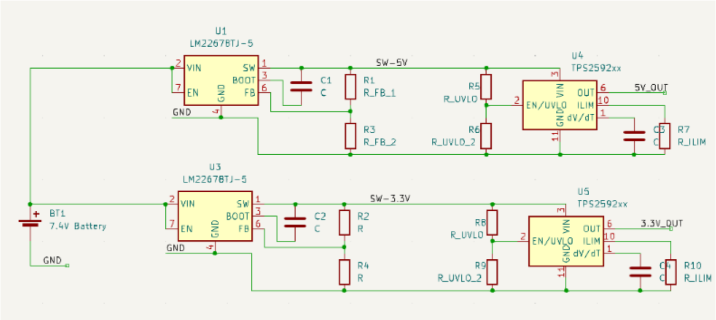


Figure 6: Power System V1

The e-Fuse components were removed to reduce cost and complexity. The LM22678 Buck Converters can use an output inductor to limit the maximum output current. A voltage divider between the V_{in} and EN pins could act as undervoltage protection. Because the safety features covered by the e-Fuse were redundant, they were removed. A professional product would still prefer to include these components for redundancy. Figure 7 shows the second model of the power system. This model adds capacitance to stabilize the ripple voltage.

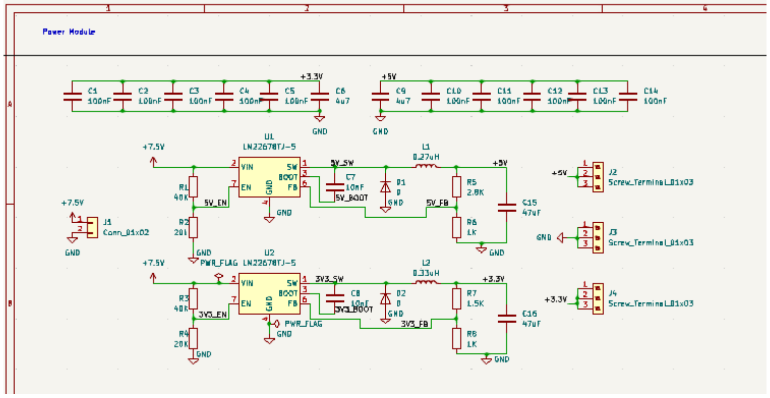


Figure 7: Power System V2

The power system was designed to use LM22678-ADJ converters. ADJ denotes that the output voltage is adjustable using the compensation loop shown in the previous figures. Mistakenly, LM22678-5.0V components were ordered instead. These components have a fixed 5 V output voltage. Upon realizing this, the correct components were ordered, but they never arrived. At this stage, we realized that the design is needlessly overcomplicated. The flaw with using linear regulators was that 7.4 V to 3.3 V at 1 A would hypothetically heat the regulator to 302 degrees Celsius. However, a linear regulator could be used to branch the 5 V buck converter output to the 3.3 V line. This would lower the cost of the system, increase component safety, and reduce design complexity.

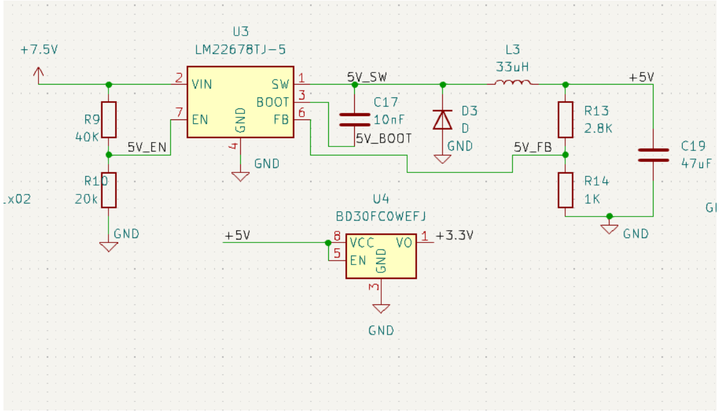


Figure 8: Power System V3

Power System V3, shown in Figure 8, was never completed due to time constraints. We proceed with power system V2. Power System V2 smoked upon connecting the 7.4 V LiPo Battery for the first time. We believe this is due to in-rush currents. However, we have no way of testing this hypothesis. If further development decided to return to a custom power supply, this would require investigation.

3. Design Details

3.1 Control Unit Details

All the subsystems needed to work together to deliver accurate feedback to the user. As the control unit, the Arduino Mega 2560 required software that would initialize all the necessary components and power them in a manner that would accomplish the requirements set at the beginning of the project.

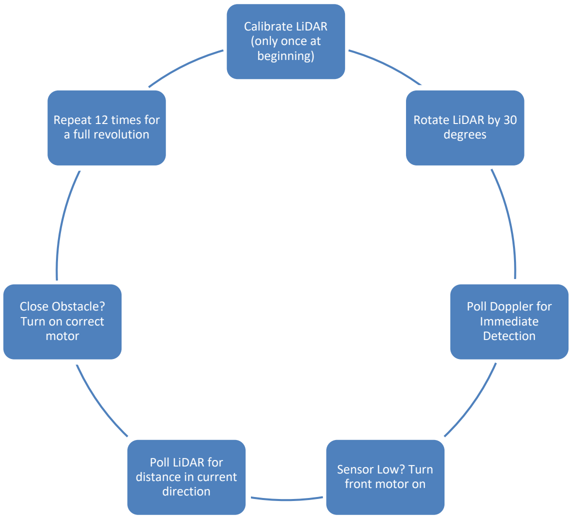


Figure 9: Code Flow Chart

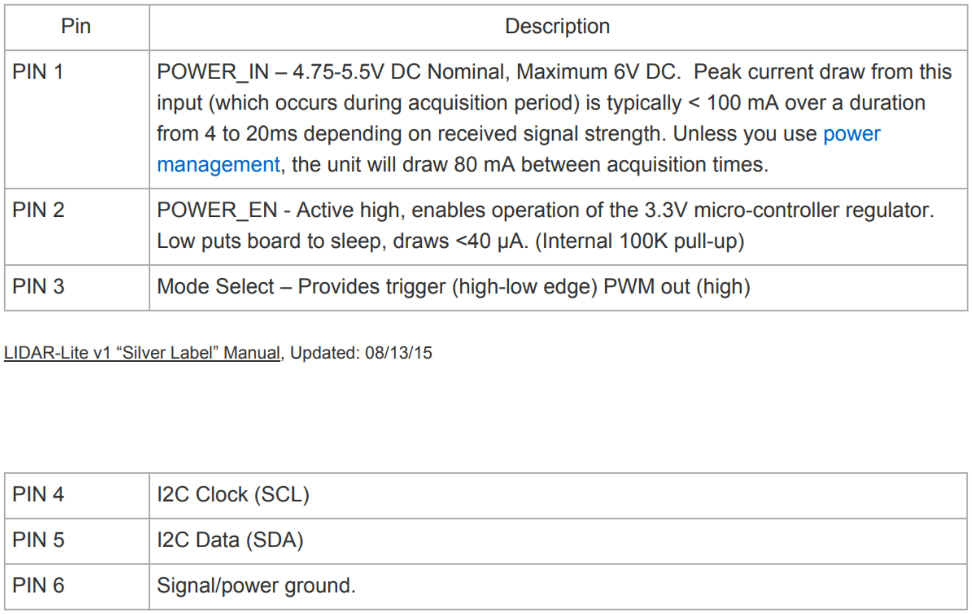
The first step was to calibrate the LiDAR by moving it until it faced the front of the hat. Once the calibration was completed, the LiDAR could now move in 30-degree increments, while the control unit polled it for the distance each step through I2C. In our high-level requirements, walls up to 5 feet away needed to be detected by the LiDAR, so if the received measurements were less than or equal to 150 cm (about 5 ft), the user would need to know. The haptic motor corresponding to the direction that the LiDAR was facing in would be turned on, sending a vibration signal. This process would be repeated 12 times for one revolution, for a 360-degree range of view.

3.2 Sensing System Details

3.2.1 LiDAR

For the project to get the distances needed to determine the behavior of the haptic motors, regardless of the microcontroller used, an I2C connection was required between the LiDAR and the Control Unit. This protocol has a setup with a single master that requests information from one or more slave devices [7]. Two lines are required for data communication across devices: the SCL (Serial Clock Pin) and the SDA (Serial Data Pin). The master device generates the SCL signal, which pulses at regular intervals and is responsible for synchronizing data transfer among all devices on the bus. The actual data is sent over the SDA line [7].

In our setup, the Arduino Mega, and previously the STM32 microcontroller, was the controller device that required information from the slave LiDAR sensor to make decisions necessary for the project's functionality. The LiDAR has six pins: Pins 1 and 6 are connected to power and ground, and pins 4 and 5 represent SCL and SDA respectively [1]. Pin 3 was not required for the project's purposes and remained unconnected.



Pin	Description
PIN 1	POWER_IN – 4.75-5.5V DC Nominal, Maximum 6V DC. Peak current draw from this input (which occurs during acquisition period) is typically < 100 mA over a duration from 4 to 20ms depending on received signal strength. Unless you use power management, the unit will draw 80 mA between acquisition times.
PIN 2	POWER_EN - Active high, enables operation of the 3.3V micro-controller regulator. Low puts board to sleep, draws <40 µA. (Internal 100K pull-up)
PIN 3	Mode Select – Provides trigger (high-low edge) PWM out (high)
PIN 4	I2C Clock (SCL)
PIN 5	I2C Data (SDA)
PIN 6	Signal/power ground.

LIDAR-Lite v1 “Silver Label” Manual, Updated: 08/13/15

Figure 10: LiDAR Pin Diagram

The I2C pins on the LiDAR were connected to the corresponding pins on the Arduino Mega.

3.2.2 Doppler

The Doppler RADAR communicates with the control unit through an analog connection. As mentioned previously, it was integrated into the project for emergency-collision detection for moving objects in front of the user. The sensor goes low when it detects a moving object in its range, and the readings are used by the software to power the haptic motors in front of the hat [3]. It operates independently of the LiDAR.

3.2.3 Hall-Effect Module

The Hall-Effect Sensor requires a pull up resistor between the power and output terminals. The recommended value is 10 KΩ. We observed through experimentation that modifying the pull up resistor will proportionally increase the range of the Hall-Effect sensor, but lower $V_{out(sat)}$. Using a 330 Ω resistor enforced a range of under 1 cm but above 10 mm. This was viable for our application [8].

3.3 Haptic System Details

The haptic motors are used to provide sensory feedback to the user. We used the Zard Zoop Vibration Coin motor. The component is rated for 2.7 – 3.3 V. The motor will survive higher voltages; however, it will begin to produce heat when the voltage exceeds 4 V. The motors are usually operated at 3.3 V, which draws approximately 60 mA. Figures X shows the

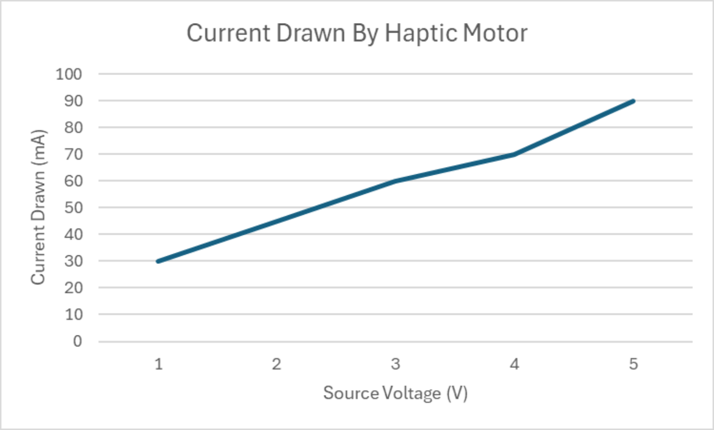


Figure 11: Current to Voltage of Haptic Motor

Each motor is driven by an IRL520N Power MOSFET. The MOSFETS prevent the Arduino from overdrawing if multiple haptic motors were on at once. They also function as voltage regulators. Because we used an analog pin to control the MOSFET, the resistance caused by transitioning between $R_{ds(off)}$ and $R_{ds(on)}$ were enough to create a voltage divider between the voltage source and motor. This limited the maximum voltage drop across the motor to a range between 2.7 V and 3.6 V.

3.4 Scanning System Details

The stepper motor gives the control unit absolute control over the operation of the scanning system. The stepper motor has four inductors that generate torque with a magnetic field. These fields are controlled with four digital pins from the control unit. The stepper motor internally uses a gear ratio to lower the speed and increase the torque.

The stepper motor's best mode of use is 15 RPM. This does not satisfy the scanning mechanism's primary requirement, which is to operate at 30 RPM. We used a 2:1 gear ratio to enable the LiDAR to spin at 30 RPM. The diameter of the larger gear is 38 mm. The smaller gear is 19mm.

The LiDAR Gears are connected by a rubber band as a belt drive.

3.5 Power System Details

The power system is broken down into two stages. The primary source powers the Arduino Mega though USB. The battery is rated 5 V and 2.1 A. The USB Input for the Arduino is limited to 500 mA.

Table 1: Current Maximum for Power System Stage 1

Component	Maximum Rated Current
Arduino Mega	500 mA

The Arduino Mega acts as the second stage of the power system. The internal linear regulators are used to form a 5 V and 3.3 V power bus. The scanning mechanism, the haptic system, and the sensing systems are all powered by Arduino’s +5 V Pin. The LiDAR takes an additional reference voltage from the Arduino’s +3.3 V pin.

Table 2: Current maximum draws from components

Component	Maximum Rated Current
LiDAR Lite	100 mA
Hall-Effect Sensor	25 mA
Doppler Radar	60 mA
Haptic Motor	60 mA
Stepper Motor	250 mA

Each pin from the Arduino is individually rated for a maximum draw of 200 mA. To avoid overdrawing, the stepper motors were powered through a motor controller and four digital pins. For the product's effectiveness, the maximum number of haptic motors active at a time is limited to two. This change ensured the Arduino could power the haptic system without an external power supply.

4. Design Verification

The final product met all the high-level requirements submitted with the design document. The final product was easy to debug. This is due to the design changes we made throughout the project heavily prioritizing consistency. Alongside design changes, the verification table had to be updated. The verification table that the final product was judged against is in Appendix A. This table includes the results of each test. The verification table included in the design document is in Appendix B.

4.1 Control Unit

The PCB Version of the control unit never progressed to the verification step. Once the control unit was changed to a development board, the control unit passed each of the final verification tests included in appendix A.

Most requirements for the control unit overlapped with the sensing and haptic feedback system, so these requirements will be discussed in detail in their appropriate sections. A requirement was added to the control unit that it could control the stepper motor. It was able to do so. The requirement to read from an accelerometer and gyroscope was removed as previously discussed.

4.2 Sensing System

The LiDAR Measurements were verified by placing the LiDAR at a known location away from a wall using a tape measure. Measurements were printed to the serial terminal from the Arduino. The results are included in Appendix A. The Doppler Radar was tested similarly. Once the control unit could perform I2C and analog reads, these components fell into place. The requirement initially required that the LiDAR could detect a wall from 5 meters away. This test was verified; however, it is not useful to the user. The more relevant threshold was 1.5 meters, which was also successfully tested.

The final version of the Hall-Effect module was equally simple to debug. We supplied the single Hall-Effect sensor with 5 V, manually placed and removed a magnet, and observed that the output voltage fell from 5 V to 0.25 mV.

The version of the Hall-Effect module with 12 sensors never passed verification. The same procedure as above was used, but it was determined that one of the Hall-Effect sensors was broken, as it could not register the magnet's presence regardless of orientation or distance. This led to us simplifying the design.

4.3 Haptic Feedback System

Early testing for the haptic motors using a bench power supply revealed that the motors could run at 5V, however they would begin to overheat and cause discomfort to the users after 10 seconds of continuous power.

The completed haptic feedback system was tested with a specific program that ran on the Arduino. The Arduino would loop between turning a specific haptic motor on for two seconds, turning the motor off, waiting one second, and then repeating the process for the next motor. This process verified the complete functionality of the haptic feedback system. All verification tests were passed.

Prior to connecting the haptic motors directly, the program was run, and the output voltage of each switching transistor was measured with a voltmeter. This ensured that the transistors were working correctly, and the output voltage drop was enough to not overheat the motors.

The major obstacle to debug was poor soldering connections between the switching transistors and the protoboard, and the inconsistency of the crimps we used before finally opting to solder the motors to the switching transistor module directly.

4.4 Scanning System

Verifying the scanning system was very straightforward. The LiDAR did spin, and the control unit could read the LiDAR through the slip ring while the LiDAR was spinning. That observation completed the verification table.

Notably, the requirement to spin the LiDAR at 30 RPM was absent from the design documents verification table. This was tested regardless. 30 RPM is slow enough to be counted manually. The motor, running at a fixed 15 RPM could spin the LiDAR at an average of exactly 30 RPM over a 10-minute period using the Hall-Effect module and an Arduino to measure RPM.

4.5 Power System

The verification table for the power system underwent as many revisions as the power system itself. The current draw thresholds for the “HVPS” and “LVPS” line changed dramatically. Notably, the haptic motors were moved to the HVPS Line caused an increase to the maximum current from the HVPS bus. The maximum acceptable ripple voltages increased likewise. Starting from Power System V3, the HVPS and LVPS current limits were combined into one 3 A maximum current draw, and the shutdown tests were merged. The final power system, using the commercially available USB charger, was tested against the verification table designed for Power System V3. The exact results can be seen in Appendix A. The only “failed” test was the 3 A maximum current draw. This shortcoming was inconsequential to the demonstration of the product but could cause a problem if somehow more haptic motors turned on than should be allowed. The final version of the product had inconsistencies where the device would shut down if the hat were physically jostled while operating. We believe that this is caused by short circuits between signal wires or transistors. Better insulation and potting the PCB would fix this.

5. Costs

The total cost to produce this project fell within the $150 USD Budget given by the department. Over the course of changing components, and parts breaking, we had to spend our own money to finish the project.

5.1 Parts

Many components for this project were sourced from the personal supply of the team members. This was to cut costs and reduce production delays from delivery times. For example, the LiDAR Sensor was provided by the university. The total combined cost of the personal parts is no less than $170.48. These components are not included in the total cost, but the unit costs are provided.

Table 3: Bill of Materials

Part		Number	Count	Manufacturer	Unit Cost ($)	Total Cost ($)
Pirate Hat		482444	2	Party City	$25.00	$50.00
Arduino Mega 2560 V2			1	Arduino	$22.88	$0.00
LidarliteV1		010-01722-00	1	Garmin	$129.99	$0.00
Doppler Radar		CQRSENWB01	1	CQRobot	$16.99	$15.99
Haptic Motors 20 PCS		B09XMXDN7M	1	Zard zoop	$11.99	$11.99
Transistors		IRL520N	12	Infineon	$1.00	$12.00
Hall-Effect		A3144	1	Eplzon	$0.35	$0.35
Resistor		330 Ohm	1	Any	$0.05	$0.00
Slip Ring		CP164	1	Comidox	$9.59	$9.59
Stepper Motor		28BYJ-48	1	DIYables	$4.99	$0.00
Skateboard Bearing		608 2RS	1	SHKI	$0.60	$0.00
Solderable Breadboard		EP-52PCB	1	EPZLON	$9.99	$0.00
Portable Battery		A1229	1	AnkerDirect	$15.00	$15.00
Total						**113.94**

5.2 Labor

We assume that the average graduate from ECE at Illinois makes $45 an hour. On average, we spent 7 hours a week on the project for the past 11 weeks. Using these numbers to calculate the cost per person, we end up with the result below:

($45/hour) x 2.5 x (7 hours/week) x 11 weeks = $8662.50

Then the total costs across all three group members would total to the following:

($8662.50/partner) x (3 partners) = $25,987.50

6. Conclusion

The Seeing-Eye Hat is in the beta stage of development. At the demo, we presented a successful engineering prototype. Engineering prototypes merge a functional ‘proof-of-concept’ build with an “attempt to mimic the appearance” of the final product. The demo model validates the core functions of the product. An ATMega2560 processor can be used to read from a rotating LiDAR sensor and translate measured distances into haptic feedback within the compact framework of a wearable device.

6.1 Accomplishments

Persistence and resourcefulness have been our team's best qualities. This project came close to failing several times throughout the development process. Making the correct judgement calls at critical moments saved the project. We used our engineering skills to adapt the design and recover from setbacks. Professionally, these soft skills will be of immense value to us. Complicated systems will never work perfectly the first time.

The systems engineering aspects of the project were successful. The team remained communicative about their progress and changes to their subsystems. This ensured that each component was designed with the greater system in mind. Integrating the subsystems was streamlined. In our internship experiences, integration, especially between electrical and mechanical systems, is often a point of failure. We did an excellent job of mitigating this.

We are proud of the prototype we were able to present. We took on a difficult project, and we rose to the occasion. Overall, this project was successful.

6.2 Uncertainties and Future Work

Continuing this project as a production prototype would require some major changes. The commercial components would need to be removed. First, we would need to implement the custom PCB with an on-board Microprocessor. The control unit would be redesigned to use an ATMega2560. The power system would be simplified and placed on-board as a custom PCB as well.

Increasing the rotation speed of the LiDAR to provide quicker feedback to the user is a high priority. Currently, the device works best while standing still for several seconds at a time. We are still unsure that the ATMega 2560 can perform LiDAR Reads fast enough to keep up with a 60 RPM Motor.

The product has not been tested in outdoor conditions, in crowded spaces, places with significant movement or under any adverse weather conditions.

Finally, the physical appearance of the product needs to be overhauled, and ideally compacted.

6.3 Ethical considerations and social impact

This product is inherently risky. The Seeing Eye Hat is an Independent Living Aid for people who are vision impaired. Despite our best intentions, the product could lead the user directly into danger. Malfunctions or improper use could prove dangerous [9]. Sections 2.1-2.6 of the ACM Code of Ethics suggest this product should have a rigorous peer and regulatory review process.

The social impact of a revolutionary independent living aid is apparent. Ideally, this product could help disadvantaged people live a safer, and more normal life. Helping those who struggle with things we take for granted is one of the most fulfilling parts of being an engineer. We wish to use our skills to make the world a better place, and our product would benefit from discussion with potential users to tailor it to their needs.

In its current form, the Seeing-Eye Hat is not ready to move past the prototyping stage due to several factors. Measurements are not recorded fast enough for this to be effective if a user were reliant on this product. The LiDAR and scanning mechanism would be prone to mechanically breaking [10]. Many of these issues come down to the size of components and processing speed. There are required design decisions between being prohibitively expensive or unwieldy.

Because of the low cost of parts used and limited time to focus on aesthetics, the presentation and structure of the current model has a large scope for improvement. The appearance of the product would be much more subtle and socially acceptable with a built-in 360-degree sensor.

While this project has its shortcomings, we believe it has a lot of potential. Future technology may make this product viable. However, it currently is not viable within an acceptable price range. Making this product useful would require technology we do not have access to. Furthermore, making this product ethical to release would require extensive review and years of study.

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Appendix A: Current Requirement and Verification Tables

Control Unit R&V

Requirements	Verification	Complete
1. The system must be able to perform reads from the LiDAR over I2C. 2. The system must be able to read from the doppler radar using the analog I/O ports.	- **Verify LiDAR Reading:** Connect the control unit to the Imaging and Sensing Unit. Observe that the control unit can successfully obtain data from the sensors.	Readings were printed to the serial terminal. This test's functionality is evident by the product working in any way.
3. Supply between 8 and 16 switching transistors with PWM signals. Observe that, given a stable 5±0.5V input, the output RMS voltage varies between 3.3±0.5V and 0V depending on the duty cycle of the PWM Pin.	- **PWM Switching Transistor Test:** Connect each switching transistors to a constant 3.3V input, and an LED output. Connect the control pin to an analog output signal on the control unit. Program the control unit to have each analog output signal use a constant frequency. Use a digital multimeter to read the output voltage of the transistor. Manipulate the PWM frequency until the output voltage of the transistor is 2 ± 0.2V Vrms. The test fails if no such frequency value exists. - **PWM Switching Transistor Current Test:** The STM Microcontroller will shut down if any analog pin exceeds 25mA of power draw. Allow the conditions from test 1 to continue for 5 minutes. If this is successful, we can verify that the current draw limits have not been reached.	This requirements completion can be verified by illustrating each motor turning on. The startup routine will show this occurs.

4. The control unit must be able to read and process distance data from the LiDAR sensor within a 10% margin of error.	- **Stationary Measurement Tolerance Test:** Connect the control unit and LiDAR sensor to a constant external power supply. Utilize the serial port to view LiDAR Read distances. Manually lower a wooden block in front of the stationary LiDAR sensor at a measured distance of one meter of distance from the front face of the LiDAR sensor and the nearest face of the block. Observe that the control unit calculates the distance of 1±0.1M. Repeat this test for 2 Meters with a measurement of 2±0.2M.	**Measuring wall distances:** **actual - 200 cm, lidar - 207 cm** **actual - 150 cm, lidar - 154 cm** **actual - 102 cm, lidar - 109 cm** **actual - 70 cm, lidar - 72 cm** **actual - 50 cm, lidar - 49 cm** **actual - 30 cm, lidar - 33 cm**
5. The surrounding area is represented internally as 8-12 zones. Each zone covers either a 30 or 45 degree slice of the 360 degree space around the wearer. The control unit must be able to detect the presence of a wall in all slices and store a value for each of them representing the distance to the nearest wall in that direction.	- **Dynamic Measurement Tolerance Test:** Allow the scanning mechanism to rotate the LiDAR Sensor. Repeat the same steps for the Stationary Measurement Tolerance Test.	This requirements completion can be verified by illustrating each motor turning on. The startup routine will show this occurs.
6. The control unit must be able to turn on the motors on or off depending on the values of LiDAR Reads.	- Position the hat such that multiple walls are present around it, with one being significantly closer than the others. - Read the values of the strengths and verify that the motor corresponding to the closest wall has the strongest strength.	This requirements completion can be verified by illustrating each motor turning on or off during runtime.

Imaging and Sensing R&V

Requirements	Verification	Complete
1. The LiDAR and Doppler sensors must provide distance measurements that have an accuracy within ±15%.	- Set objects at predetermined distances away from the user. - Take the distances read by the LiDAR and Doppler sensors and calculate the percentage error between those and their corresponding actual distances. - Make sure that this value is within ±15%.	**Measuring wall distances:** **actual - 200 cm, lidar - 207 cm** **actual - 150 cm, lidar - 154 cm** **actual - 102 cm, lidar - 109 cm** **actual - 70 cm, lidar - 72 cm** **actual - 50 cm, lidar - 49 cm** **actual - 30 cm, lidar - 33 cm**
2. The LiDAR sensor should be able to detect walls within 2 meters.	- **Maximum Distance Test:** Hold the LiDAR Sensor directly against a wall as close to a wall as possible. Walk backwards with the LiDAR sensor until the sensor stops detecting the wall, or the sensor is over 10 meters away from the wall.	**See table above**
3. The Hall-Effect Sensor is able to determine when the LiDAR is facing the front of the hat within ±10 degrees.	- **Hall-Effect Test:** Manually move the LiDAR to the front of the hat. Use a protractor to determine the active zones for the Hall-Effect Sensor to be within ±10 degrees of each sensor placed	This requirements completion can be verified by illustrating the startup routine rotating the LiDAR to face front before operation begins. The startup routine will show this occurs.

Scanning Mechanism R&V

Requirements	Verification	Complete
1. The slip ring a brushed motor should be able to rotate the LiDAR continuously for at least 10 minutes.	- **Isolated Motor Longevity Test:** Set a timer for 10 minutes and connect the scanning mechanism to an external variable power supply set to 5V. This should rotate the LiDAR sensor. If the LiDAR is still rotating by the time the 10 minutes are up, then this test will be considered passed. - **Integrated Motor Longevity Test:** Set a timer for 10 minutes and connect the scanning mechanism to the power subsystem's high voltage bus. This should rotate the LiDAR sensor. If the LiDAR is still rotating by the time the 10 minutes are up, then this test will be considered passed.	The brushed motor was replaced with a stepper motor. Specifically, the stepper motor turns a gear, which turns the LiDAR. Whenever the scanning mechanism receives 5V of power, the LiDAR does rotate for 10 contiguous minutes.
2. The slip ring should be able to facilitate I2C transmissions between a microprocessor and the LiDAR Sensor.	- **Isolated Slip Ring Test:** Connect the data-out I2C components to the control unit or external computer. Then, connect the scanning mechanism to an external variable power supply set to 5V. This should rotate the LiDAR sensor. Validate that measurements can still be read from the LiDAR sensor while rotation is in progress. This validates that the slip ring works effectively.	This requirements completion can be verified by illustrating the LiDAR spinning without problems. The startup routine will show this occurs.

Haptic Feedback R&V

Requirements	Verification	Complete
1. Between 8 and 16 LRA Motors exist. Each switching transistor should be connected to one LRA Motor. The switching transistor accepts PWM input. The PWM controlled switching transistors enable each motor to switch between “High” and “Low” strength.	- **Isolated Switching Transistor Test:** Connect the modular haptic feedback system to an Arduino development board. Measure the voltage input to a singular motor with a digital multimeter. Supply a PWM signal to the switching transistor such that the voltage is measured at a predetermined “high” value. Manually change the PWM signal such that the digital multimeter reads a predetermined “low” value. Validate that the motor is operating at a noticeable lower strength under this new condition. Repeat this test for all motors. - **Integrated Switching Transistor Test:** Connect the modular haptic feedback system to the Control Unit. Measure the voltage input to a singular motor with a digital multimeter. Place a wooden block two feet in front of the LiDAR sensor. Observe that the voltage is measured at the predetermined “low” value under these conditions. Place the block one foot in front of the LiDAR sensor. Ensure that the voltage is read at the predetermined “high” value under these conditions. Repeat this test for all motors.	A separate “Haptic Test” code was written and executed that turns each haptic motor on for 2 seconds, and then turns the motor off. This functions as“High” and “Low” strength. This test was performed again once the motors were mounted to the hat. It was also successful. Once integrated with the LiDAR, the Integrated Switching Transistor test was performed successfully.
2. Each LRA Motor must draw under 80mA during normal operation.	- **Current Draw Test:** Utilize a digital multimeter to measure the current draw of each motor while active in “high strength” conditions. Allow the operation to continue for 5 minutes. If at any point the measured current exceeded 80mA for more than five seconds, the test is failed.	During the haptic motor test above, an ammeter was connected to measure the draw of the total haptic module. For each motor's time operating, the maximum observed current was 76mA.
3. The haptic feedback provided by motors should have an intensity strong enough to be picked up by the user.	- **Distinct Difference Test:** A sample size of 15 students experience wearing the hat under “near” and “far” conditions and report feeling a distinct difference in motor strength.	15 students from the ECE445, ECE385 and Mechanical Engineering Building were asked to wear the hat. The individual haptic motor test was performed. Each student could feel each motor. It was reported that some motors were stronger than others.

Power R&V

Requirements	Verification	Complete / Comments
1. The power system must accept a 7.4V input and output a 5±0.5V power bus	- **Short Term Voltage Test:** A digital multimeter will be used to measure the voltage difference between the power and ground outputs of the power PCB. This will verify that the system can perform its most basic functions.	No Load condition output voltage measures between 5.2V and 5.4V.
2. The "High Voltage" line supports a maximum current draw of 3A.	- **Less than worst case power test:** Power all 12 existing haptic motors at full strength for 10 minutes. This will draw 0.9A on average. If the system encounters no unexpected behaviors, the test is passed.	The system supports a measured current draw of 800mA This was measured by powering multiple motors and measuring the output until failure.
3. If the maximum current threshold of 3A is exceeded, the buck converter must isolate the voltage source from the rest of the assembly.	- **Short Circuit Test:** Short the ground and power buses intentionally. Observe that the system shuts down and restarts once the short is removed.	Test performed as described. The system shut down instantly without damage to the arduino mega that was connected.
4. The system will safely shut itself down when the battery is depleted to under 5V.	- **UVLO Test:** Supply the power system using a variable power supply. Begin operating with a supply voltage of 7.4V. Every minute, decrease the voltage by 1V until the output voltage becomes zero. The test is successful if the output terminals shut down before the battery voltage drops below 4.5V. This test fails if system shutdown occurs	Test performed as described.

	within half an hour of beginning the test.	
5. The power system must enable the finished product to operate continuously and uninterrupted for half an hour.	**Worst Case Power Consumption Test:** Connect the power system to a "complete" finished product. This consists of the following features: • All haptic motors included in the final product are manually set to their full power. • Each sensor is recording and transmitting data to the Microprocessor as validated through the serial port • The scanning mechanism is spinning continuously Connect an oscilloscope to measure the voltage and current draws from each power bus. Ensure they stay within "stable" ranges as defined in the previous tests throughout the entire half an hour duration.	

Appendix B: Old Requirements and Verification Tables

Original Control Unit R&V

Requirements	Verification	Notes
1. The system must be able to perform reads from the LiDAR and the Doppler Radar over I2C. It must also be able to export data to an external device over the serial port.	• **Verify LiDAR Reading:** Connect the control unit to the Imaging and Sensing Unit. Connect the serial port to an external microcontroller that supports a serial terminal print stream. Observe that the control unit can successfully obtain data from the sensors.	Minor changes were made. The Doppler radar does not use I2C, it uses analog I/O ports.
2. Supply between 8 and 16 switching transistors with PWM signals, each drawing under 25mA, in order to reduce the input voltage from 3.3 ± 0.2V to an output voltage of 1.0 ± 0.2Vrms.	• **PWM Switching Transistor Test:** Connect each switching transistors to a constant 3.3V input, and an LED output. Connect the control pin to an analog output signal on the control unit. Program the control unit to have each analog output signal use a constant frequency. Use a digital multimeter to read the output voltage of the transistor. Manipulate the PWM frequency until the output voltage of the transistor is 2 ± 0.2V Vrms. The test fails if no such frequency value exists. • **PWM Switching Transistor Current Test:** The STM Microcontroller will shut down if any analog pin exceeds 25mA of power draw. Allow the conditions from test 1 to continue for 5 minutes. If this is successful, we can verify that the current draw limits have not been reached.	The test was changed to read “Vrms” because a switching transistor can not regulate output voltage in the manner described in the design document. The input voltage to the switching transistor is changed to 5V to compensate for voltage loss between the drain and source pins of the transistor. These losses were not considered when writing the original R&V Table. The output voltage has been changed to measure 3.3±0.5V for “High” strength and 0±0.5V for “low” strength.
3. The control unit must be able to read and process distance	• **Stationary Measurement Tolerance Test:** Connect the control unit and LiDAR sensor	Requirement unchanged

data from the LiDAR sensor within a 10% margin of error.	to a constant external power supply. Utilize the serial port to view LiDAR Read distances. Manually lower a wooden block in front of the stationary LiDAR sensor at a measured distance of one meter of distance from the front face of the LiDAR sensor and the nearest face of the block. Observe that the control unit calculates the distance of 1±0.1M. Repeat this test for 2 Meters with a measurement of 2±0.2M.	
4. The surrounding area is represented internally as 8-12 zones. Each zone covers either a 30- or 45-degree slice of the 360 degree space around the wearer. The control unit must be able to detect the presence of a wall in all slices and store a value for each of them representing the distance to the nearest wall in that direction.	• **Dynamic Measurement Tolerance Test:** Allow the scanning mechanism to rotate the LiDAR Sensor. Repeat the same steps for the Stationary Measurement Tolerance Test.	Requirement Unchanged
5. The control unit must be able to turn on the motors with magnitudes of strength inversely proportional to the magnitude of the values read in Requirement 4.	• Position the hat such that multiple walls are present around it, with one being significantly closer than the others. • Read the values of the strengths and verify that the motor corresponding to the closest wall has the strongest strength.	The “inversely proportional” requirement conflicted with the Haptic Feedback systems requirements for binary values. The control unit can output analog signals that are inversely proportional to the readings. However, because of the transistor's properties, the motors cannot respond to these PWM Values as described in the test. Instead, a different timing for distances was used, with longer activations being closer.
6. The measured distances are adjusted to compensate for the directional travel recorded by the accelerometer.	• Position the user directly across from a wall and have them move forward towards the wall. • Measure distances before and after the user moves.	The accelerometer has been removed from the project after receiving approval from Professor Fliflet.

Original Imaging and Sensing R&V

Requirements	Verification	Complete
1. The LiDAR and Doppler sensors must provide distance measurements that have an accuracy within ±15%.	- Set objects at predetermined distances away from the user. - Take the distances read by the LiDAR and Doppler sensors and calculate the percentage error between those and their corresponding actual distances. - Make sure that this value is within ±15%.	Requirement unchanged
2. The LiDAR sensor should be able to detect walls within 5 meters.	- **Maximum Distance Test:** Hold the LiDAR Sensor directly against a wall as close to a wall as possible. Walk backwards with the LiDAR sensor until the sensor stops detecting the wall, or the sensor is over 10 meters away from the wall.	The device can do this, but this is entirely useless to the user. 5 feet was changed to 5 meters instead of 2 meters erroneously when we submitted the design document. This has been corrected.
3. The Hall-Effect Sensors are able to determine when the LiDAR is facing the front of the hat within ±10 degrees.	- **Hall-Effect Test:** Manually move the LiDAR to the front of the hat. Use a protractor to determine the active zones for the Hall-Effect Sensor to be within ±10 degrees of each sensor placed	Minor wording changes. The brushed motor was replaced with a stepper motor to keep track of the rotation better. One Hall-Effect sensor is still used for calibration. This feature works consistently.
4. The Gyroscope can provide 3-axis positioning data to the microcontroller over I2C.	- Connect the gyroscope to an external development board. Initialize an I2C connection and ensure that it can transmit data effectively. Rotate the gyroscope 360 degrees in each direction to validate the full range of values that can be recorded.	The gyroscope and accelerometer were removed from the project after receiving approval from Professor Fliflet.

Original Scanning Mechanism R&V

Requirements	Verification	Notes
1. The slip ring and brushed motor should be able to rotate the LiDAR continuously for at least 10 minutes.	• **Isolated Motor Longevity Test:** Set a timer for 10 minutes and connect the scanning mechanism to an external variable power supply set to 5V. This should rotate the LiDAR sensor. If the LiDAR is still rotating by the time the 10 minutes are up, then this test will be considered passed. • **Integrated Motor Longevity Test:** Set a timer for 10 minutes and connect the scanning mechanism to the power subsystem's high voltage bus. This should rotate the LiDAR sensor. If the LiDAR is still rotating by the time the 10 minutes are up, then this test will be considered passed.	The brushed motor was replaced with a stepper motor.
2. The slip ring should be able to facilitate I2C transmissions between a microprocessor and the LiDAR Sensor.	• **Isolated Slip Ring Test:** Connect the data-out I2C components to the control unit or external computer. Then, connect the scanning mechanism to an external variable power supply set to 5V. This should rotate the LiDAR sensor. Validate that measurements can still be read from the LiDAR sensor while rotation is in progress. This validates that the slip ring works effectively.	Requirement unchanged

Original Haptic Feedback R&V

Requirements	Verification	Notes
1. Between 8 and 16 LRA Motors exist. Each switching transistor should be connected to one LRA Motor. The switching transistor accepts PWM input. The PWM controlled switching transistors enable each motor to switch between “High” and “Low” strength.	• **Isolated Switching Transistor Test:** Connect the modular haptic feedback system to an Arduino development board. Measure the voltage input to a singular motor with a digital multimeter. Supply a PWM signal to the switching transistor such that the voltage is measured at a predetermined “high” value. Manually change the PWM signal such that the digital multimeter reads a predetermined “low” value. Validate that the motor is operating at a noticeable lower strength under this new condition. Repeat this test for all motors. • **Integrated Switching Transistor Test:** Connect the modular haptic feedback system to the Control Unit. Measure the voltage input to a singular motor with a digital multimeter. Place a wooden block two feet in front of the LiDAR sensor. Observe that the voltage is measured at the predetermined “low” value under these conditions. Place the block one foot in front of the LiDAR sensor. Ensure that the voltage is read at the predetermined “high” value under these conditions. Repeat this test for all motors.	Unchanged requirement
2. Each LRA Motor must draw under 80mA during normal operation.	• **Current Draw Test:** Utilize a digital multimeter to measure the current draw of each motor while active in “high strength” conditions. Allow the operation to continue for 5 minutes. If at any point the measured current exceeded 80mA for more than five seconds, the test is failed.	Unchanged requirement
3. The haptic feedback provided by motors should have an intensity strong enough to be picked up by the user.	• **Distinct Difference Test:** A sample size of 15 students experience wearing the hat under “near” and “far” conditions and report feeling a distinct difference in motor strength.	Unchanged requirement

Original Power System R&V

Requirements	Verification	Change Log
4. The power system must output two power buses at 5V +/- 0.2V and 3.3V +/- 0.1V.	- **Short Term Output Voltage Test:** A digital multimeter will be used to measure the voltage differences between the "High Voltage" and "Low Voltage" power buses. This test will be performed for each power bus. This will verify that the system can perform its most basic functions.	Changes to the design have removed the requirement for a 3.3V buck converter. The main reason for the 3.3V bus was to power the Haptic Motors. The switching transistors have an inherent voltage drop that performs this function. Increasing the current through the 5V buck controller increases the acceptable ripple voltage.
5. The "High Voltage" line supports a maximum current draw of 0.5A. This is based on the sum of constant current draws by each sensor and microcontroller.	- **High Voltage Current Draw Test:** Connect a 10 ohm resistor between the "High Voltage" terminal, and ground. This will draw 0.5A from the source. The resistor must be rated to dissipate over 2.5W. Measure the voltage between the terminals as well as the current through the resistor over a 10 minute period with an oscilloscope. The test is a success if the voltage remains between 4.7 and 5.3V, and the system draws between 0.4A and 0.6A through the entire duration. The specific target is 5V and 0.5A.	The minimum required current for the 5V line increased to 1A before the Individual Progress Report. The 3.3V and 5V lines from the design document were merged as described in the previous test's comments. The 1A and 1.5A maximums were combined to 3A maximum for the entire assembly. This design is safer because the entire system will now shut down under short circuit conditions instead of just one branch.
6. The "Low Voltage" line must support a maximum current draw of 1.5A. This calculation is based on a maximum 16 LRA Motors, which are rated for 60mA each, with an additional 0.5A for other features.	- **Low Voltage Current Draw Test:** Connect a 2.2 ohm resistor between the "Low Voltage" terminal, and ground. This will draw 1.5A from the source. The resistor must be rated to dissipate over 5W. Measure the voltage between the terminals as well as the current through the resistor over a 10 minute period with an oscilloscope. The test is a success if the voltage remains between 2.7V and 3.5V and the system draws between 1.2A and 1.7A throughout the entire	The 3.3V line has been removed, as discussed in requirement 1. The only remaining 3.3V signal is the reference voltage to the LiDAR Sensor. This can be provided by the Arduino Mega's 3.3V output pin. The lower voltage drop and required current would make a linear regulator viable for this functionality if the Arduino were removed and the STM32 was reinstated.

	duration. The specific target is 3.3V and 1.5A.	
7. If either of the maximum current thresholds are reached, the buck controller will safely disconnect the battery from the other systems. This feature also protects the components from short circuits, and from backfeeding.	- **Low Voltage overdraw test:** Measure the voltage between the “Low Voltage” terminal and ground using an oscilloscope. Observe that the voltage difference is approximately 3.3V. Connect a 1 ohm resistive load. This will draw 3.3A from the source. The resistor must be rated to dissipate over 10W. Observe on the oscilloscope that the voltage across the terminals becomes 0V within one second of connecting the load. Observe that the current draw does not become negative. - **High Voltage overdraw test:** Measure the voltage between the “High Voltage” terminal and ground using an oscilloscope. Observe that the voltage difference is approximately 5V. Connect a 5 ohm resistive load. This will draw 1A from the source. The resistor must be rated to dissipate over 5W. Observe on the oscilloscope that the voltage across the terminals becomes 0V within one second of connecting the load. Observe that the current draw does not become negative.	Minor wording changes were made. There is now only one maximum threshold.
8. The system will safely shut itself down when the battery is depleted to under 5V.	- **Lifespan and Undervoltage Test:** This tests the undervoltage lockout features of the buck controller. Connect the resistive loads from test 2 and 3 to their respective terminals. Measure the voltage across the battery, low voltage, and high voltage terminals. Monitor the system until the voltage across both the low and high voltage terminals is zero. The test is successful if the output	Requirement unchanged.

	terminals shut down before the battery voltage drops below 4.5V. This test fails if system shutdown occurs within half an hour of beginning the test.	
9. The power system must enable the finished product to operate continuously and uninterrupted for half an hour.	• **Worst Case Power Consumption Test:** Connect the power system to a “complete” finished product. This consists of the following features: • All haptic motors included in the final product are manually set to their full power. • Each sensor is recording and transmitting data to the Microprocessor as validated through the serial port • The scanning mechanism is spinning continuously Connect an oscilloscope to measure the voltage and current draws from each power bus. Ensure they stay within “stable” ranges as defined in the previous tests throughout the entire half an hour duration.	Requirement Unchanged.