ProxiPole

An Electronic Walking Stick for the Visually Impaired

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Table of Contents

1. Introduction
1.1 Objective 2
1.2 Background 2
1.3 High-level Requirements 3

2. Design
2.1 Design Procedure 4
2.2 Design Details 5
2.3 Functional Overview 7
2.4 Haptic Intensity Calculations 9
2.5 Tolerance Analysis 10

3. Requirements and Verification 12
4. Cost Analysis 15
5. Safety and Ethics 17
5.1 General Ethics 17
5.2 Laser Safety 17
5.3 Lithium-Ion Batteries 17
6. Conclusions 18
6.1 Successes 18
6.2 Failures 18
7. References 20
8. Appendix 21

1. Introduction

1.1 Objective

One of the main objectives of creating an enhanced walking stick capable of sensing surrounding objects is to create an electronic system that is portable, reliable, and durable enough to be mounted on the lightweight walking sticks currently in use. Many of the attempts at enhanced walking sticks have only included single-dimensional information, like the object range, and typically only include one proximity sensor.[1] These solutions really only give the user rudimentary range and direction information. The inclusion of an array of sensors can give the user an even better understanding of exactly where, and how far, the detected obstacle is. This can provide a significant improvement over current solutions.

The goal of ProxiPole is to allow its users to have an enhanced understanding of their surroundings by using electronic sensors. ProxiPole will make use of a small array of laser proximity sensors, haptic motors, and audio devices to detect incoming obstacles and alert the user to their approximate range and direction. This information will allow the user to have a heightened awareness of their environment, and by extension afford them the opportunity to make better informed decisions.

1.2 Background

Currently, there are approximately 253 million people in the world who suffer from some form of vision loss, with 36 million of those people being completely blind.[2] Although many blind people are able to adapt very well to a life without sight, there are still many issues they have to deal with that normally-visioned people do not even think twice about. Auxiliary issues associated with blindness include non-24-hour sleep-wake disorder,[3] depression,[4] anxiety,[5] and many more. One of the main obstacles that blind people face is navigating their surroundings, especially in unfamiliar environments. A lack of situational awareness can pose serious threats to the safety of blind people, and many tools have been created to aid them in increasing that awareness. One of the main tools that the visually impaired use is a walking stick. They sweep the stick out in front of them to physically probe for objects, allowing them to avoid obstacles and to navigate other changes in their environment. Because of the issues that blind people face, it’s a moral imperative to help them as much as possible to make their lives easier.

1.3 High-Level Requirements

1. The user will be alerted of the horizontal distance from the obstacle via the vibration motors' intensities, detecting a range of 1.5 meters and below. The intensity will increase in magnitude when the user starts closing in to the obstacle.
2. The electronic walking stick should be equipped to detect and alert the user of any obstacle and its direction, that lies within a sector range of 100° ahead of it.
3. The stick should account for changes in relative yaw in case the user's torso is turned and the stick is away from its 0° starting angle.

Figure 1: ProxiPole - Finished Product

2 Design

2.1 Design Procedure

In order to create this product, consideration must be given to two primary areas: the physical design of the system, and its electrical architecture. The physical design must take into consideration a few main requirements: that it is durable, strong, reliable, but also lightweight enough to be held for many hours on end. There are multiple conceivable ways that this can be done, but the primary determining factor in making the system lightweight will be in the materials that are used. Most walking sticks are built using either aluminum or carbon fiber and can usually be folded up or telescoped into a smaller form.

For this project, simple PVC pipe with a rubber-foam outer coating will be used for the stick's material simply because it is cheap to prototype this design and will suffice in terms of strength and durability. Because it's expected that the PVC pipe will be heavier than typical aluminum/carbon fiber solutions, some of the heavier components like the motherboard PCB and the battery pack will be offloaded to a belt that the user will wear. This belt will also serve to contain the haptic motors that will provide the user feedback on the direction and distance to detected objects.

For the electrical architecture, this design will make use of an entirely digital system (versus an ad hoc analog solution). In order to meet our requirements of a 100° field of view (FOV), we need to design this system to contain an array of sensors that will span across the full 100°. The number of sensors needed will simply be dependent on the FOV of each individual sensor. There are also a few different types of sensors that could be chosen, each with pros and cons. Infrared LEDs could be used, however they typically have very small ranging distances and can be easily fooled by ambient infrared light. Sonic lasers could also be used. Using sound to range objects is particularly attractive because most objects in everyday life do not vary in their sonic reflectance to a great degree, and these sensors are typically able to reliably detect objects of any shape or size (which is especially true when considering the large field of view of sonic sensors). Lastly, another option is to use LIDAR sensors. LIDAR for the purposes of this project is among the best options because it provides reliable and precise measurement of objects, and also has well-defined fields of view, whereas sonic sensors do not.

The PCB that will house the central components will "glue" the entire electrical system together. An ATMega328 socket-type microcontroller will be attached onto the PCB. The reason for using the socket type instead of the SMD-mounted microcontroller is because it is convenient to program the chip on an Arduino (which natively provides a USB interface for programming and serial output), then place it back onto the PCB. Although it was convenient for prototyping and programming, it was found that inserting and removing the microcontroller multiple times tended to weaken the pins and caused them to frequently break. It is for this reason that it might be more desirable to integrate a USB connection with an SMD type microcontroller.

2.2 Design Details

2.2.1 Block Diagram

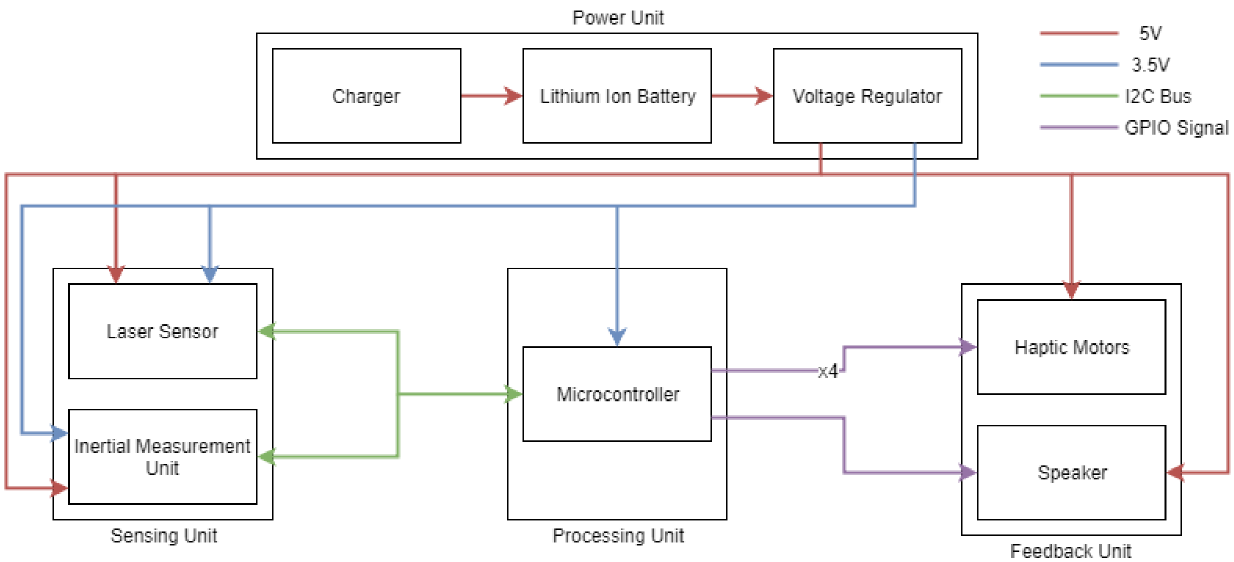

Figure 2: Block Diagram of ProxiPole

This design provides our system with the four main components that are needed: a power system to power the components, a sensing system that will provide spatial and locality information, a microcontroller to process the input, and the feedback system that will report to the user information about their surroundings.

2.2.2 Circuit Schematic

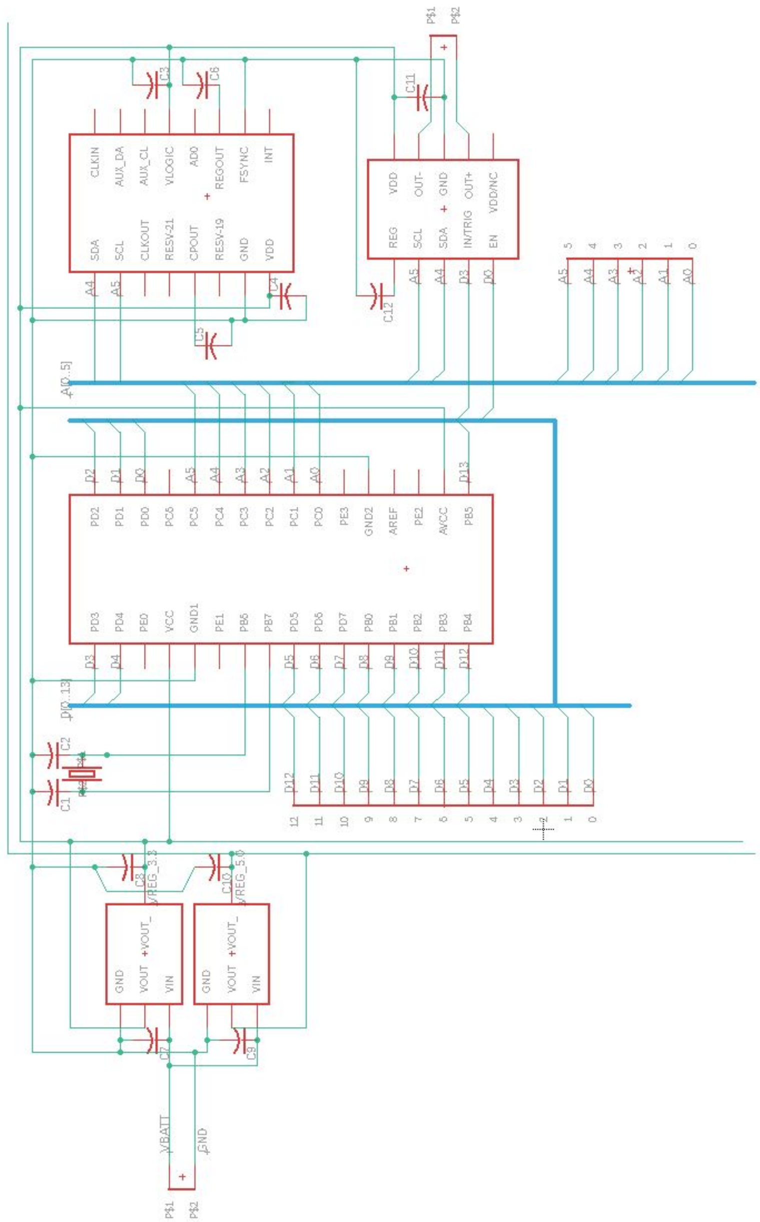

Figure 3: Schematic of Main Circuit

This is the Main circuit board schematic which contains the voltage regulator, microcontroller, IMU, and motor driver. Terminals will be used for connecting the external laser sensors.

2.2.3 Physical Design

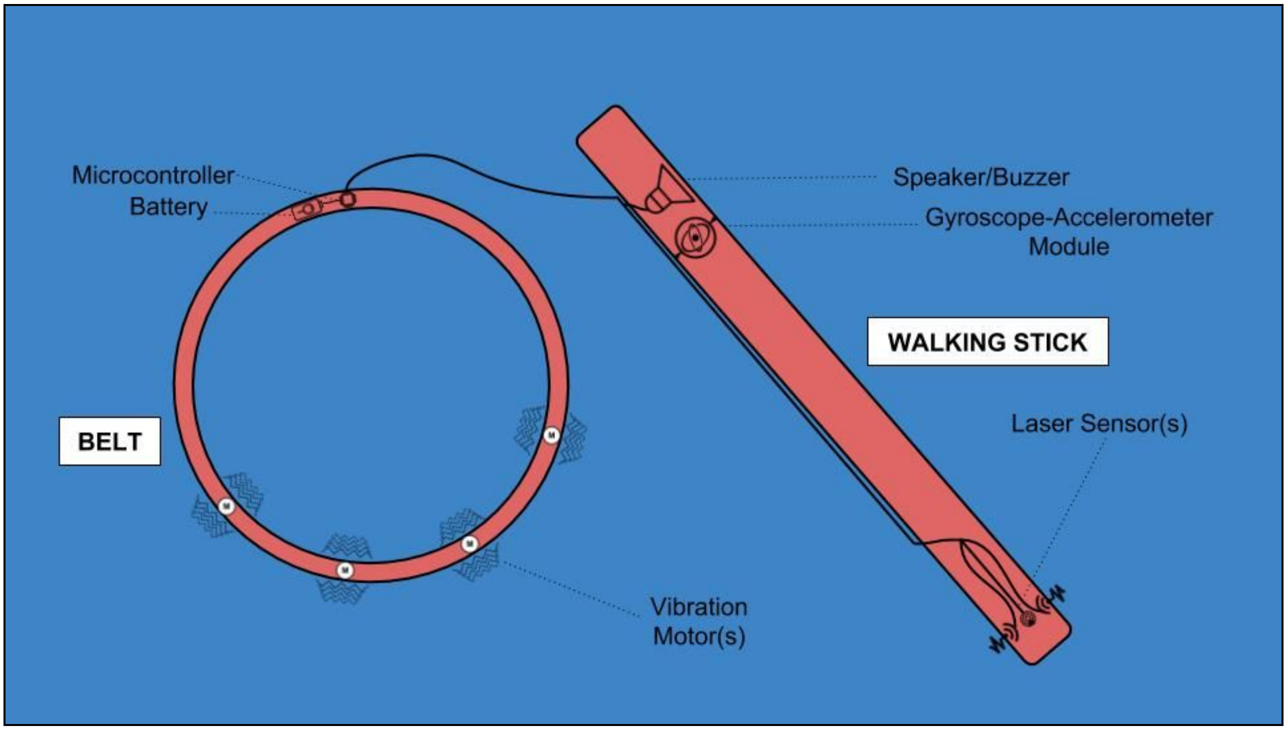

Figure 4: Physical Design of ProxiPole

We aim to to have 2 physical modules comprising our final device. These would be a belt unit, that will be worn around the user's waist, and the actual electronic walking stick, which will be handheld. In order to minimize the weight of the walking stick, the main circuit component and power source will be fitted onto the belt itself, as depicted in Figure 4. Lastly, our walking stick will also have a grip that would make it easier to hold on to.

2.3 Functional Overview

The block diagram is separated out into 4 main components, the power system, the sensing system, the microcontroller, and the feedback system.

2.3.1 Power System

The power system will provide the power necessary to drive both the digital circuitry (including the sensors and the microcontroller) and the haptic motors. The power will be supplied with a bank of rechargeable Lithium Ion batteries that are recharged through a proprietary lithium ion charger. We do not intend to implement our own charging system because of the dangers associated with accidentally overcharging Li-ion batteries. The power system will also need to be regulated through a power regulator. The regulator will ensure that each of the components in the entire system are receiving the voltage necessary for safe operation, as well as providing electrical shorting safety mechanisms (implemented with simple fuses).

2.3.2 Sensing System

The sensing system will provide our product with sensing capabilities of the outside world. There will be two main types of information provided: object locality/object distance through the use of infrared laser sensors, and system orientation through the use of electric gyroscopes and accelerometers, in a circuit called Inertial Measurement Unit (IMU). The IMU will be used primarily to determine the true direction of detected objects relative to the user as the user sweeps the stick back and forth. The reason why this is needed is because we require the system to activate the haptic motor that points to the actual location of the detected object, irrespective of the orientation of the walking stick at any point in time.

The IMU will be a 3-axis system that uses a combination of accelerometers and gyroscopes to determine spatial orientation and location. The board will feature an on-board digital processor that uses the MotionFusion algorithm to interpret raw sensor data into spatial location that will be sent to the microcontroller via I2C. The algorithm is factory-implemented on the chip, so our product will not have to directly interact with the algorithm.

2.3.3 Microcontroller

The microcontroller will be the central component that translates incoming sensor data into user feedback. This chip will receive incoming input data from the IMU and the proximity sensors, and implement a basic algorithm to determine the position of the detected object relative to the user and activate the corresponding haptic motor. If the chip detects an object is within a predetermined threshold, it will sound an audible alarm. The program that is executed on the microcontroller will be written in C and compiled to the native architecture of the chip. Additionally, some minor circuitry will be needed to implement a clock for the microcontroller.

2.3.4 Feedback System

The feedback system will be what provides the user with information on object range and locality. It will be a fairly simple system that comprises of 4 haptic feedback motors, and one audible speaker mounted on a wearable belt. These devices will be connected to and controlled by the microcontroller. Each of the haptic motors is driven by a driver circuit, which itself is toggled on and off by the microcontroller. This driver circuit is necessary because the microcontroller is not capable of sinking enough current to the motors.

2.4 Haptic Intensity Calculations

The four haptic motors on the system must be activated according to some mathematical function that accounts for 5 separate variables: the distances reported by each individual laser, and the relative yaw, calculated from the difference of the yaw values reported by each individual IMU. The function that will describe the intensity of each motor can be created in a somewhat ad hoc manner, and is highly implementation-dependent.

The function that was created is based off of the Gaussian distribution. The function will have four Gaussian terms, one for each laser, that describes the contribution each laser has to a specific motor's intensity. The figure below shows a graphical representation of the formula for motor 0 (the left most). The x-axis is the relative yaw of the stick to the user's torso in degrees, 0 degrees being directly ahead and positive degree values being in the clockwise direction. The y-axis is the motor's intensity in percent of its maxima.

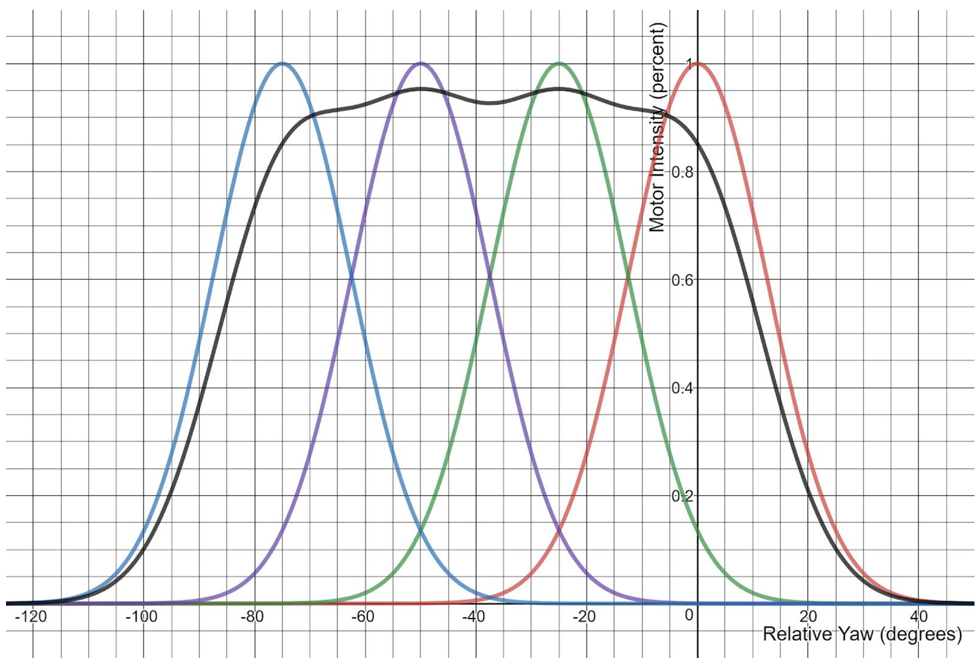

Figure 5: Example intensity curve

Each of the colored lines represent the contribution that each individual laser has on motor 0's overall intensity. The black line represents the addition of each distribution, scaled to be within the range of 0 to 1. The red term is the left-most laser, while the blue term is the right most. Intuitively, one can clearly see that if the user begins to yaw the stick in the counterclockwise direction, the intensity of the motor begins to rely on different lasers as the angle increases in the negative direction. Similarly, each motor will have same function but with the terms appropriately offset in the x-axis. Also note that the amplitudes of each term is an inverse relationship of the distance reported by the corresponding laser.

The formula below is the corresponding mathematical description of motor 0's intensity.

$$I_0 = \frac{1}{d_0} e^{-(x-\mu_0)^2/2\sigma^2} + \frac{1}{d_1} e^{-(x-\mu_1)^2/2\sigma^2} + \frac{1}{d_2} e^{-(x-\mu_2)^2/2\sigma^2} + \frac{1}{d_3} e^{-(x-\mu_3)^2/2\sigma^2}$$

$$\begin{gathered} d_i = \text{Distance reported by Laser i} \\ \text{x} = \text{Relative Yaw} \\ \mu_0 = \text{Motor 0 Offset - Laser 0 Offset} \\ \mu_1 = \text{Motor 0 Offset - Laser 1 Offset} \\ \mu_2 = \text{Motor 0 Offset - Laser 2 Offset} \\ \mu_3 = \text{Motor 0 Offset - Laser 3 Offset} \\ \sigma = 12.5^\circ \end{gathered}$$

It's worthy to note that it appears that the intensity function will diverge to infinity if any of the laser distances reports a value of 0. This is of course a problem in theory, but in practicality it seems as if the lasers used in this project never report 0 even if they are directly covered by some object. It was not explored how the ATMega328 responds when dividing by zero, so future iterations of this project will either need to implement software-level protection against this, or thoroughly document the behavior of the chip to see if a division by zero would result in a system collapse (versus, perhaps, simply a temporary overflow of some register).

2.5 Tolerance Analysis

The primary conduit for successful operation of this system is its ability to reliably detect obstacles within a certain horizontal and angular range. The required angular range of 100 degrees in front of the sensing array can be met almost universally by simply adjusting the number of sensing units attached to the pole. Intuitively, if sensors are used that have a very small angular range of sensing, the required 100 degrees is achieved by adding more sensors. The number of sensors *n* required with individual sensing ranges *r* is simply

Eq 1

$$n = \frac{100}{r}$$

However, it must also be noted that an upper bound is placed on the number of sensors the microcontroller can poll every second. In typical I2C communications, 2 bytes are reserved for header information (device addressing, acknowledgements). 7 of these bits are reserved for addressing, so theoretically only 128 devices may be connected to a single bus. The remaining message payload is determined by the individual device's requirements. The upper bound for the number of sensors a given microcontroller can handle is thus:

$$n_{max} = min(\frac{s}{x}, 128) \quad \textit{Eq 2}$$

Where n_{max} is the theoretical upper bound, *s* is the number of transmitted bytes required to perform a poll of a single sensor (including headers), and *x* is the number of bytes per second the microcontroller can send through the I2C bus. This value itself is a function of clock speed and the corresponding microcontroller's MIPS speed.

The ATMega 328p microcontroller we will use will be clocked using a 15 MHz oscillator. According to the 328p datasheet, it is capable of executing 20 MIPS (million instructions per second) at a 20 MHz clock. This means that at 15 MHz, it should be capable of executing 15 MIPS. An extremely liberal estimate is that each poll of a sensor requires 500,000 instructions. Dividing the MIPS performance by the number of instructions per poll, we see that the upper bound for the number of sensors capable of being polled is

$$15,000,000 \,/\, 500,000 = 30$$

The field of view (FOV) of the VL53L1CXV0FY/1 is 27 degrees. Using equation 1, we see that we would need 3.7 sensors to cover the overall 100 degree FOV. This is well within the upper limit discovered using liberal estimates for the polling instruction cost.

3 Requirements and Verification

3.1 Power System

Requirements	Verification
1. The power system should be able to maintain two voltage sources: 3.3V, and 5.0V with a tolerance of ±10% for each voltage. *(Passed Requirement)*	1. Disconnect the power supply from the rest of the circuit. Then: a. Draw 900mA from the 5V source and measure the amount of voltage fluctuation b. Disconnect from 5V, and draw 900mA from 2.5V and measure fluctuation. c. Disconnect from 2.5 and draw 900mA from 3.3V source, measuring voltage fluctuation. If at any step in this process the voltage remains within 10% of the target voltage, the verification succeeded.
2. The power system's output must be fault protected so that no more than 1 amp of current can be drawn at any given point in time. *(Failed Requirement)*	2. Draw 1.5A from each source individually to see if the system faults for singular sources. Then, draw 0.75A from each source at the same time to test that drawing 1.5A in total across all sources will also engage fault protection. If both of these tests succeed, then verification for the fault protection has succeeded.

3.2 Sensing System

Requirements	Verification
1. The range-finding sensors should be able to detect an object within a cone around the array of 100 degrees (+-27 degrees in either direction from each sensor) *(Passed Requirement)*	1. Define 0° as directly in front of the sensor, -90° as left, and 90° as right. Move a white piece of paper starting from -90° to 90°, keeping half a meter from the sensor. Note the angle at which the sensor begins to detect the object, and at which it ceases detection. If difference ≥ 100°, this verification succeeded.
2. The sensing system should be able to detect obstacles with a 90% success rate at a distance of 1 meter in broad daylight. *(Passed Requirement)*	2. Print out a grayscale gradient paper. Repeatedly, place and remove the piece of paper in front of the sensors, 1 meter away. If the system fails to detect at most 1 time, the verification succeeded.
3. The combined sensing system should be able to detect an object and deterministically identify an angle of detection relative to the holder of ProxiPole. *(Passed Requirement)*	3. Have a blindfolded user hold the ProxiPole. Place a piece of paper 0.5 meters from the system, within the 100° cone of sensing. Repeat for 4 random angles. The blindfolded user will point in the direction, the haptic motors indicate. If the user fails to point directly at the paper during any of the tests, the verification failed.

3.3 Microcontroller

Requirements	Verification
1. The microcontroller must be capable of addressing 4 separate laser sensors through its GPIO pins with the I^2C protocol using a shared bus. *(Passed Requirement)*	1. This verification is inherent in the design of the circuitry. If all 4 lasers can be communicated with using a shared I^2C bus, then the verification succeeded.

2. The microcontroller must be fast enough to allow it to poll all 5 sensors (4 proximity and 1 IMU) and activate the 5 feedback units (4 haptic motors and 1 audible alarm) at least 4 times a second. *(Passed Requirement)*	2. The microcontroller will be polling the sensors and activating the feedback system in an infinite loop. Pick a free GPIO pin and program the microcontroller to toggle the pin at the beginning of its loop. Connect this pin to an oscilloscope and measure the frequency at which the pin oscillates. If it oscillates ≥ 4 times/sec, the verification succeeds.

3.4 Feedback System

Requirements	Verification
1. The feedback system should be able to activate our motors given a microcontroller input. *(Passed Requirement)*	1. Test to see that all of the motors are activated according to the direction of the detected object by individually placing a white piece of paper 10cm in front of each sensor.
2. The speaker should emit a characteristic tone that will indicate an imminent collision given microcontroller input. *(Failed Requirement)*	2. Place a white piece of paper 1 meter away from the sensors and decrease its distance until the paper is touching the sensors. Note the point at which the audible alarm sounds. This point should be no less than 20 cm away from the sensors.
3. The driver circuit must be capable of activating all haptic motors at full power. *(Passed Requirement)*	3. Place a white piece of paper 10 cm away from all sensors and test to see that all 4 haptic motors are activated. Confirm full power by measuring peak PWM voltage to each motor.

4 Cost Analysis

Part Name	Quantity	Cost / Item	Cost	Cost (Mass Production)
3-Axis Gyro/Accelerometer IC - MPU-6050	1	$12.95	$12.95	$11.25
Arduino A000066 (ATmega328)	1	$22	$22	$20.00
Laser Proximity Sensors (VL53L1CXV0FY/1)	4	$6.43	$25.72	$22.00
Vibrating Mini Motor	12	$1.95	$23.40	$21.60
Motor Driver	4	$6.95	$27.80	$27.00
CSM-7X SMD CRYSTAL	1	$0.46	$0.46	$0.46
Voltage Regulator	1	$0.44	$0.44	$0.44
Terminal Blocks (Phoenix Contact 1935187)	7	$0.80	$5.60	$5.25
Lithium Ion Battery - 3.7v 2000mAh	2	$12.50	$25	$22.5
0805 2.2 kOhm Resistor	20	$0.084	$1.68	$0.80
0805 0.1uF Capacitor	20	$0.195	$3.90	$0.084
0805 1.0uF Capacitor	20	$0.081	$1.62	$0.064
0805 4.7uF Capacitor	20	$0.127	$2.54	$0.10
0805 2.2nF Capacitor	20	$0.046	$0.92	$0.036
0805 10nF Capacitor	20	$0.131	$2.62	$0.048
28 pin IC socket	5	$0.71	$3.55	$0.47
Total			**$163.69**	**$135.30**

In addition to the above cost of the inner product circuitry, we would like to include the price of other physical material included in the development of ProxiPole. A waterproof belt, that would hold the main PCB unit and the battery pack, would cost $10 and the hollow stick capable of housing inner wiring, sensors and speakers would cost about $15. However, for mass production these would be purchased at a subsidised cost of $7 and $10 respectively.

With 3 members on the team, who put in 12 hours/week valued at $35/hr, we spent 16 weeks building the prototype. This would add up to a labor cost of:
3 *x* (12 hours)/week *x* 16 weeks *x* 35 $/hour = **$20,160**

The total cost, including our development cost and labor cost, would be around $20,323.69

5 Safety and Ethics

5.1 General Ethics

This project was motivated by the lacking technology to aid the visually impaired. Part of our ethical requirements is to hold the health and safety of other people with high regard[6]. By tackling this project, we will be improving the safety and overall quality of life for the blind. Our goal is that the project will make navigation easier for the blind while reducing the amount of stress they get from that navigation, especially in new environments. Additionally, according to the 9th item from the IEEE code of ethics, we should be avoiding the injury of others in their property[6]. Our project will take every precaution in ensuring the safety of the users especially in those areas of highest risk such as those highlighted in the next section.

5.2 Laser Safety

The range finding sensors we propose to use are a class 1 laser of the infrared spectrum. Our design will use several of these sensors which could be pointed by the user in any general direction. According to IEC 60825-1:2007, Such class 1 lasers are completely safe under normal operating conditions and even if viewed by the naked eye under normal telescopes and microscopes[7]. With such a classification we can be assured that the lasers will be harmless in our application.

5.3 Lithium-Ion Batteries

Lithium batteries can be very dangerous if care is not taken to insure proper functionality. In general these batteries can overheat and become damaged very easily from a short circuit. Our design will take this into consideration and strive to eliminate this possibility. Furthermore, lithium batteries can be damaged from over discharge and overcharge. We plan on implementing over discharge protection into our power subsystem and purchase a 3rd party charger to keep the battery within acceptable voltages.

6 Conclusions

6.1 Successes

During the course of the project, we were able to successfully integrate an object detection LIDAR array with the haptic motor drivers. The final system provided the users with an intuitive notion of the direction and distance of surrounding objects. The system was also able to calculate the appropriate intensity of the motors using a simple inverse linear relationship for reported laser distances. The project was also able to separately demonstrate the conceptual functionality of the entire laser-IMU-motor system separately on an Arduino, in addition to verifying the theoretical soundness of the core mathematical mappings of laser distances and relative yaw to haptic intensities.

6.2 Failures

There were a few failures in this project that prevented the full integration originally specified in the design document. The primary failure surrounded the IMU devices. When these were integrated into the larger system with our PCB motherboard, we noted that a critical I2C communication error occured that caused the entire bus to indefinitely hang. The figure below shows this failure.

Figure 6: SDA/SCL Plots of the I2C Protocol

The way that I2C works is that a master device will broadcast the address of the desired device onto the bus. When the corresponding device hears its address, it will pull the SDA line low (yellow) when the SCL line (green) transitions from high to low. Each of these communications are 9 clock cycles long: 8 cycles for transmitting one byte of data, and 1 cycle for an acknowledgement. The previous figure shows how the IMU properly acknowledged receipt of its address, but it prematurely sends an acknowledgement on the 8th clock cycle, rather than the 9th. Because the master device never receives an acknowledgement from the IMU on the expected 9th cycle, it then hangs.

The team was not able to determine exactly what caused this behavior. The fact that the IMUs worked correctly leads to the belief that there is something inherently wrong with the PCB itself, or with some incompatibility between the PCB and the IMU. There are a few leading theories that might this failure. One of the possibilities is that the 3.3v VDD and logic causes instability in the IMU chip. Another possibility is that there is some interference in the I2C bus, however this hypothesis is not well supported because snapshots of the SDA/SCL lines show no such interference. Lasty, it is possible that there is something inherently wrong with the IMU chip. Even though the manufacturing specifications state that it is compatible with 3.3v logic, it might be that the chip acts incorrectly when connected to 3.3v versus 5v logic.

References

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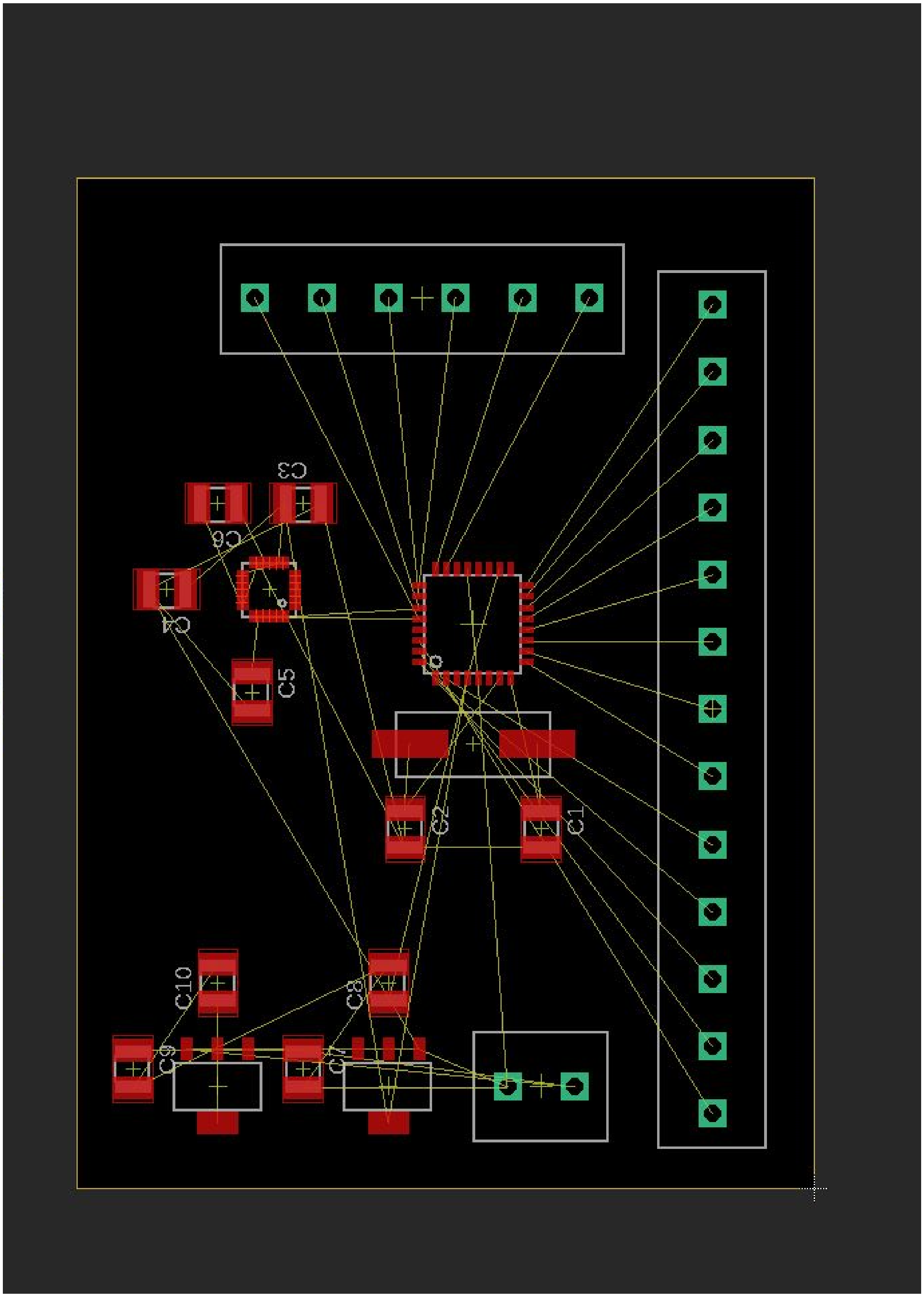
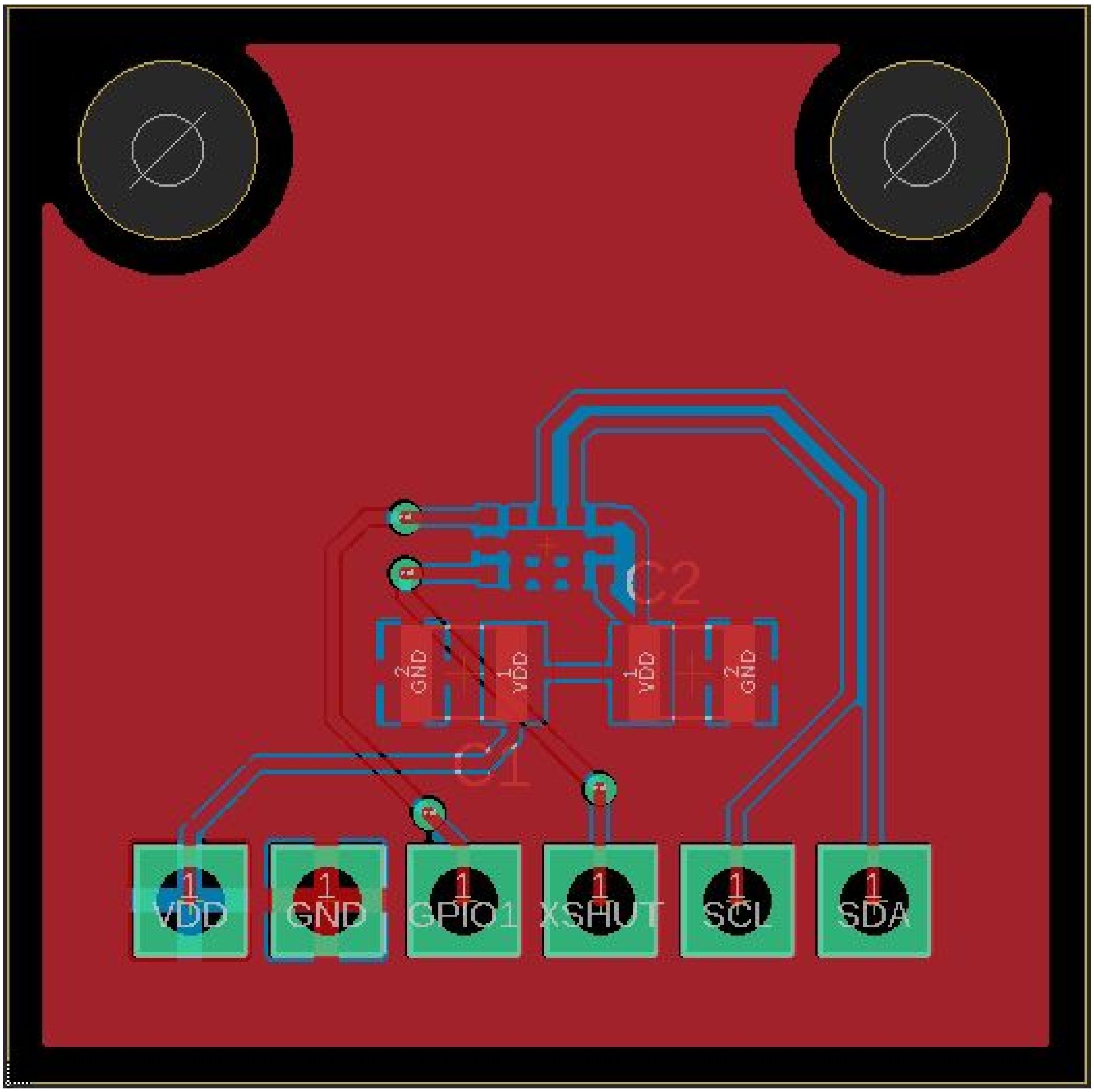
Appendix

Links to datasheets:

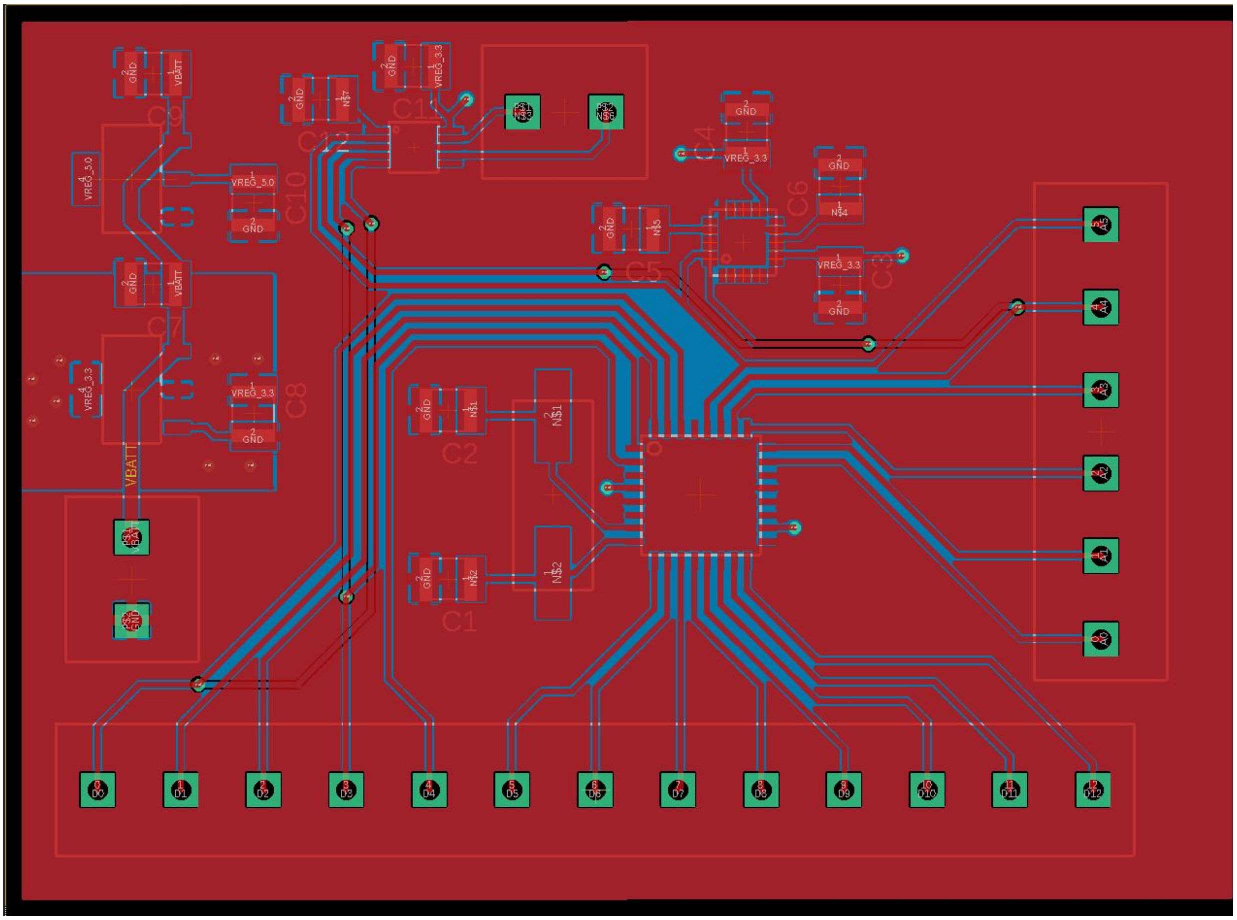
- 3-Axis Gyro/Accelerometer IC - MPU-6050 (https://cdn.sparkfun.com/datasheets/Components/General%20IC/PS-MPU-6000A.pdf)
- Laser Proximity Sensors (VL53L1CXV0FY/1) (https://www.mouser.com/datasheet/2/389/en.DM00452094-1315090.pdf)
- CSM-7X SMD Crystal (https://www.mouser.com/datasheet/2/122/csm-7x-1299.pdf)
- Voltage Regulator (https://www.mouser.com/datasheet/2/389/ldl1117-1156241.pdf)
- Terminal Blocks (Phoenix Contact 1935187) (https://media.digikey.com/pdf/Data%20Sheets/Phoenix%20Contact%20PDFs/1935187.pdf)
- Atmega328p microcontroller http://ww1.microchip.com/downloads/en/DeviceDoc/ATmega328_P%20AVR%20MCU%20with%20picoPower%20Technology%20Data%20Sheet%2040001984A.pdf
- Charger: https://www.sparkfun.com/products/10217
- Battery: https://www.sparkfun.com/products/13855



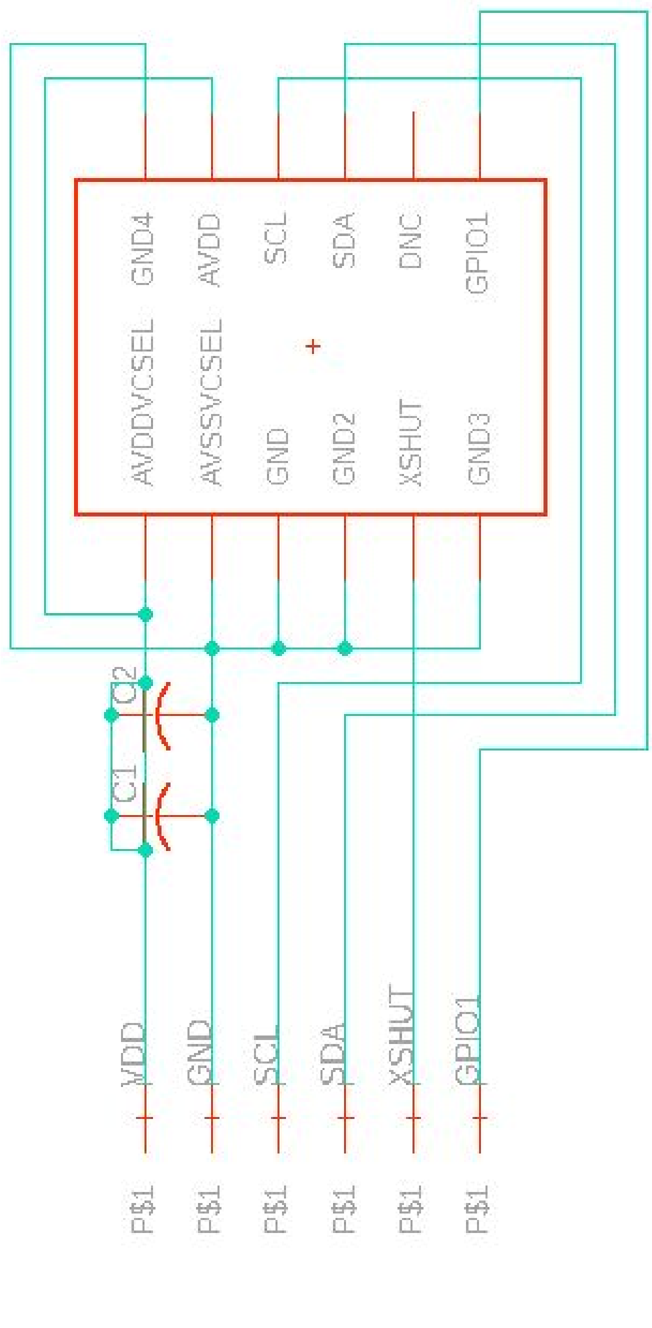
A: PCB Layout of Circuit, 75mm x 55mm



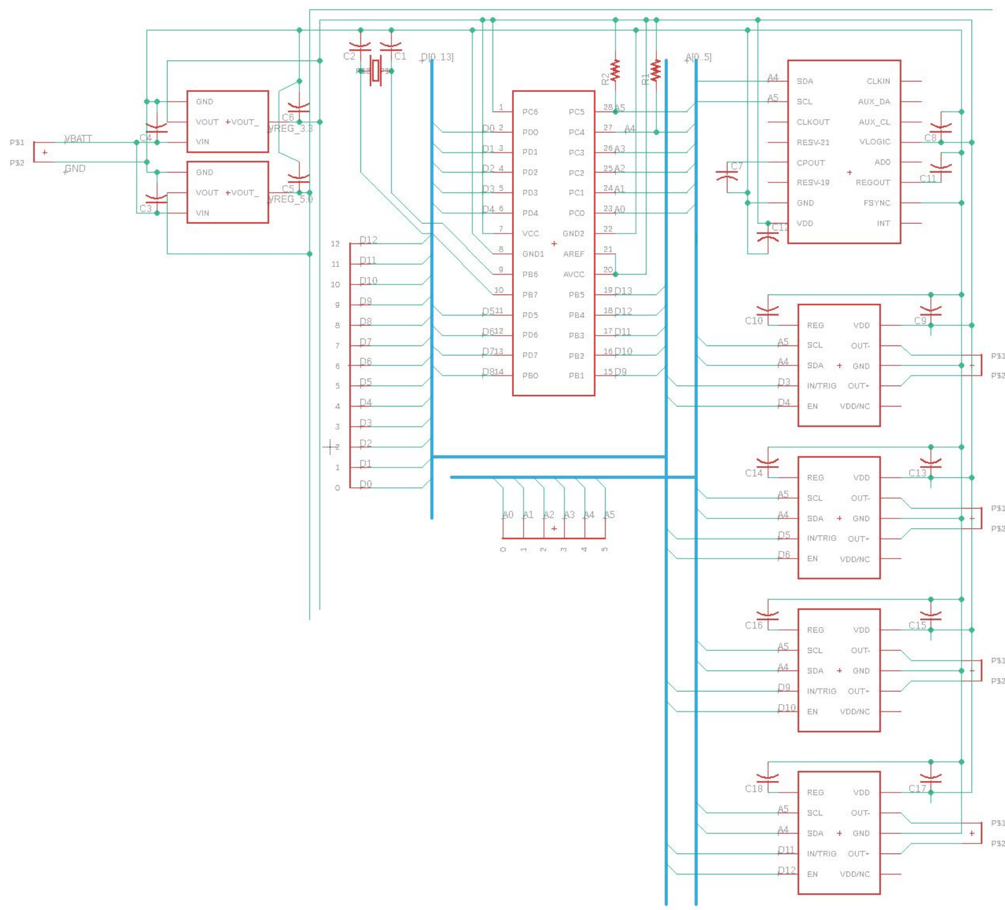
B: Laser sensing board



C: Bottom & Top layer PCB trace layout



D: Schematic of laser sensor breakout board



VBATT
GND
PS1
PS2
VOUT
VIN
VREG_3.3
VREG_5.0
D[0..13]
A[0..5]
R1
R2
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
C11
C12
C13
C14
C15
C16
C17
C18
PC6
PD0
PD1
PD2
PD3
PD4
VCC
GND1
PB6
PB7
PD5
PD6
PD7
PB0
PC5
PC4
PC3
PC2
PC1
PC0
GND2
AREF
AVCC
PB5
PB4
PB3
PB2
PB1
SDA
SCL
CLKOUT
RESV-21
CPOUT
RESV-19
VDD
CLKIN
AUX_DA
AUX_CL
VLOGIC
AD0
REGOUT
FSYNC
INT
REG
IN/TRIG
EN
OUT-
OUT+
VDD/NC