SATELLITE:

Speed Adjusting, Track Exploring, Load Locating, Intelligent Train Engine

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Abstract

Toy trains are a quintessential hobbyist item, ingrained in the lives of conductors around the world since the early twentieth century. The following decades witnessed a decline in this electric entertainment due to an aging toy train hobbyist community and a lack of innovation in the industry to intrigue the younger generations. The goal of this project is to create an innovative train through improving its reliability when faced with non-ideal conditions (obstacles and unsmooth sections of track) and introducing a track-mapping and train-locating feature. This report provides details for the design of the toy train system and the verification of its modules.

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1. Introduction

1.1 Purpose

The electric model train has captivated audiences for more than a century, from its early days in toy store displays at the turn of the 20th century — capturing the imaginations of children for whom in-home electricity was still rare — to its growth as a popular hobby between the 1930s and 1950s [1]. Yet, there is still room for innovation in the modern era to improve the electric model train for future generations of children and even hobbyists. A major issue still confronting model trains is that of derailment. For instance, when the train's speed is too great over a certain segment of the track, typically a corner, the train will often derail. Another instance of chaos arises from the accidental placement of another toy or an object in the path of the train, leading to collision, derailment, and possible damage to the train. We strove to reconcile this problem to better protect expensive model trains from accidental damage as well as serve as an educational toy for children to learn of simple sensor technology.

In order to combat derailment, we employed two techniques - speed limit signs and obstacle detection. To stop a model train from moving too fast over a segment of track, a speed limit sign may be placed near the track to slow the train. Using an Infrared (IR) sensor on each sign and an IR LED on the train, the sensors identify when the train passes the corresponding speed sign and communicate to a speed control unit that adjusts the voltage on the tracks to reach the proper speed. To achieve obstacle detection, two laser time-of-flight (ToF) sensors are placed on the front of the train to locate oncoming objects as well as their distance from the train and communicate to the speed control unit if the train needs to be stopped. An additional third element of innovation on the electric model train is path-mapping. One radio frequency (RF) receiver detects the signal emitted by the RF transmitter on the train and serves to synchronize the three ultrasonic receivers, which are placed along the track in a triangular formation, by beginning a measurement of the amount of time elapsed until the ultrasonic signal is detected at each receiver. Once each receiver detects the ultrasonic signal, the distance between transmitter and receiver is calculated using the known speed of sound. These distance measurements and a trilateration technique are combined to estimate the location of the train and map the path it follows. If we were to continue this project, we would look to provide more customizability to the tracks to allow for new track layouts for children to explore and map as well as a general broadening of a digital interface to the train to appeal to this tech-driven generation.

1.2 Objectives

- Train must detect obstacles on the track and halt motion 98% of the time.
- Train must detect speed limit signs and adjust speed accordingly 98% of the time.
- Train must map the track and estimate the position of the train within a 7.5 cm radius of its actual position.

2. Design

2.1 Block Diagram

The train system requires five main components to successfully accomplish all the high-level requirements: a power unit, a speed control unit, a speed detection unit, an obstacle detection unit and a track mapping unit as shown in Figure 1.1. For clarity, Figure 1.2 shows the components that are on the train, and Figure 1.3 shows the components that are off the train. A physical design is also included in Appendix D, page 31.

The power unit ensures that the entire train ecosystem is powered to perform obstacle and speed detection, speed control, and track mapping.

The speed control unit uses a full-bridge driver for the motor to allow for Pulse Width Modulation (PWM). A PWM input is used to vary the speed of the train. The speed control unit receives data from both the obstacle detection and speed detection units. When the obstacle detection unit indicates an obstacle, the speed control unit stops the train by turning off the output of the bridge to the motor. When the speed detection unit encounters a speed limit sign corresponding to a preset speed, the speed control unit adjusts to that speed by altering the duty cycle of the PWM signal. If a signal is triggered from both the obstacle detection and speed detection units, the obstacle detection unit takes priority. Once the obstacle detection unit no longer detects an obstacle, then the speed from the speed detection unit is adjusted.

The speed detection unit uses an IR LED mounted on the train along with IR sensors on each speed limit sign. If a sign's IR sensor sees the LED on the train, the speed detection unit sends the speed associated with the sign to the speed control unit and has the speed of the train adjusted accordingly.

The obstacle detection unit uses two laser time-of-flight (ToF) sensors on the train. When both ToF sensors see an object 20 cm ahead, the obstacle detection unit sends its detection to the speed control unit to stop the train before collision.

The track mapping unit utilizes a trilateration algorithm that uses an RF and ultrasonic transmitter, located on the train, and a single RF receiver and three ultrasonic receivers located along the track. In each time interval, the train sends out an RF and ultrasonic pulse. The RF receiver detects the RF pulse almost instantaneously (on the order of microseconds at the scale of the track) which begins a timing measurement. The ultrasonic pulse travels to each of the receivers at the speed of sound. When the pulse is received at each ultrasonic receiver, the elapsed time is recorded. Using the time and speed of sound, the distance of the train to each receiver is calculated. These three distances are inputs to the equations that determines the (x,y) coordinates of the train at any given point in time. This data is then transferred to an external computer via universal serial bus (USB) connection, where a serial listener displays the map on the monitor.

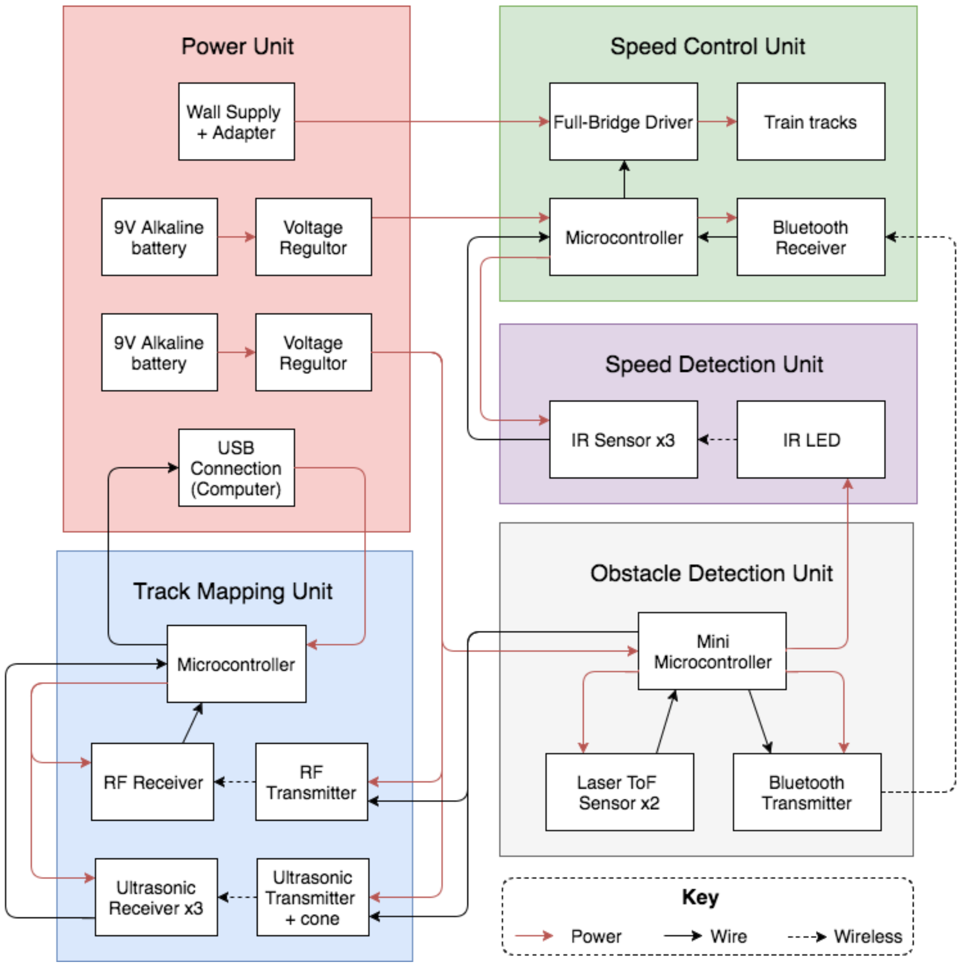

Figure 1.1: High Level Block Diagram

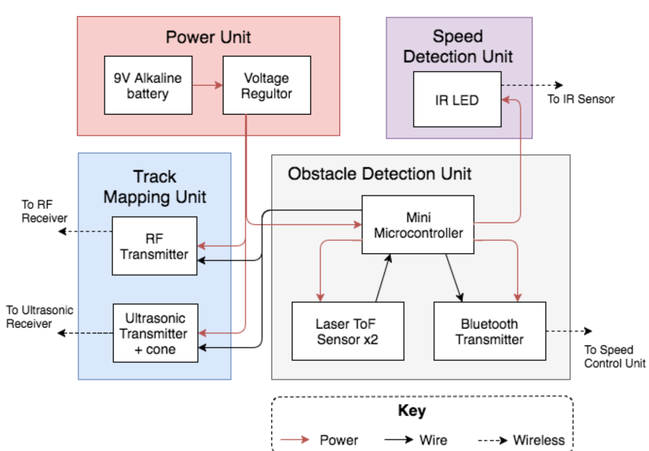

Figure 1.2: On-Train Block Diagram

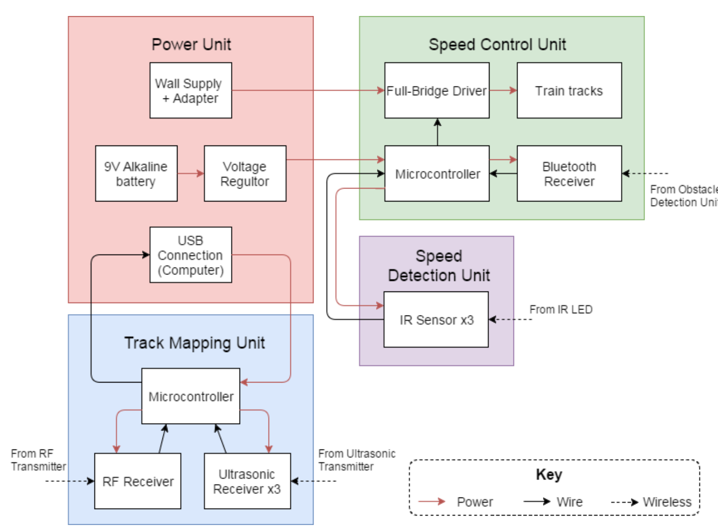

Figure 1.3: Off-Train Block Diagram

2.2 Power Unit

The power supply is essential for controlling the train's speed, detecting obstacles, and mapping out the track. A 9 V alkaline battery with a voltage regulator powers the mini microcontroller, RF transmitter, and ultrasonic transmitter on the train. A separate battery and regulator powers the speed control unit microcontroller. A connection to a laptop via USB powers the track mapping unit. A 16 V wall supply powers the full-bridge driver of the speed control unit which is ultimately used to power the tracks. The Bluetooth transmitter and receiver, the IR sensors, the laser ToF sensors, the RF receiver, the ultrasonic receivers, and the integrated circuit (IC) used in the full-bridge driver are all supplied with power from the microcontroller which they connect to.

2.2.1 9 V Alkaline Battery and Voltage Regulator

One of two 9 V batteries supplies power to the on-train PCB. The Arduino Pro Mini, which is used on the train PCB, has a built-in voltage regulator that steps down the input voltage to 5 V. The 5 V output powers all of the components on the train and is regulated down to 3.3 V to power the Bluetooth module. The second 9 V battery supplies power to the speed control PCB. The 9 V is stepped down to 5 V through a voltage regulator to power the microcontroller and associated logic. The regulated 5 V is input to a 3.3 V regulator that powers the Bluetooth module.

2.2.2 Universal Serial Bus (USB) Connection

The microcontroller in the track mapping unit is powered via USB, using an FTDI (Future Technology Devices International) basic breakout board. A USB connection to a computer is used to send serial data to display the track mapping on the computer's monitor. This USB connection provides power to the unit as well.

2.2.3 Wall Supply

The provided wall supply unit in the train set comes with a 16 VDC output rated for up to 1000 mA. This unit supplies the full-bridge driver in the speed controller unit which then powers the tracks of the train. The resistance of the tracks and the track-train wheel connection is measured to be around 60 Ω. Thus, we ensured the wall supply is able to supply around 0.267 A at 16 V during train operation.

2.3 Speed Control Unit

The speed control unit is responsible for adjusting the speed of the train by varying the duty cycle of a PWM signal powering the train tracks. This unit consists of a microcontroller that communicates with a Bluetooth receiver and IR sensors to determine at which speed the train should be operating. In addition, the full-bridge driver is used to supply the tracks with power. Once the required speed for the train is determined from the data the microcontroller receives, it selects the correct duty cycle of a PWM signal that controls the transistors of the bridge circuit. 16 V from the wall supply powers the bridge and a PWM signal from the microcontroller controls the bridge to modulate this input such that a 16 V PWM signal is output to control the motor. By varying the duty cycle, the circuit varies the average voltage supplied to the motor and thus speed of the train. Figure 2 illustrates the circuit implemented for speed control.

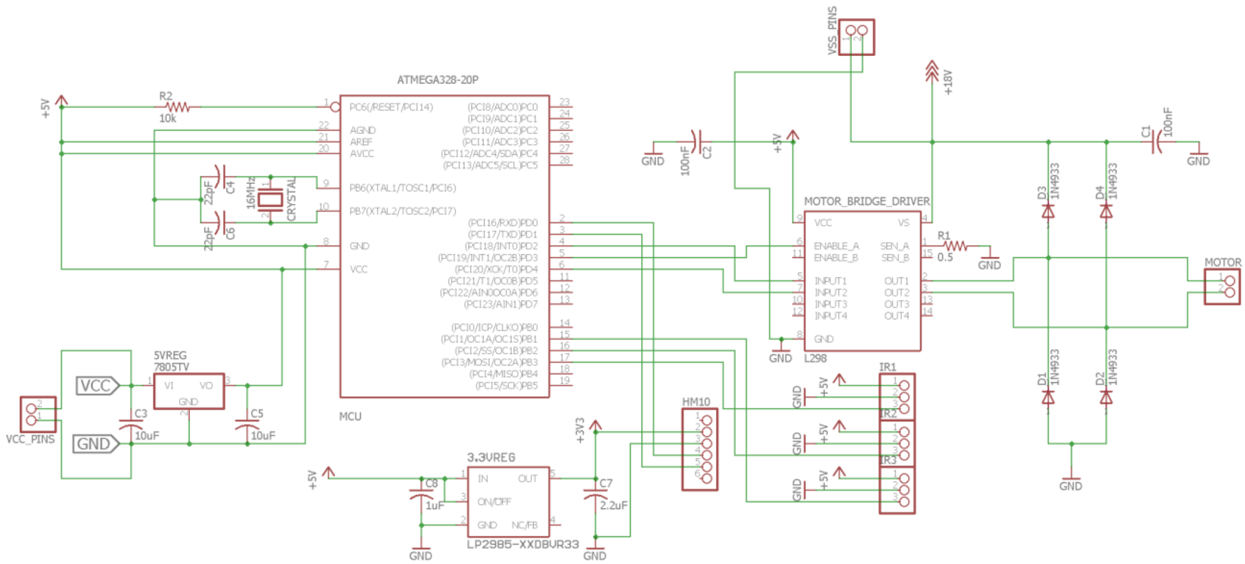

Figure 2.1: Speed Control Schematic

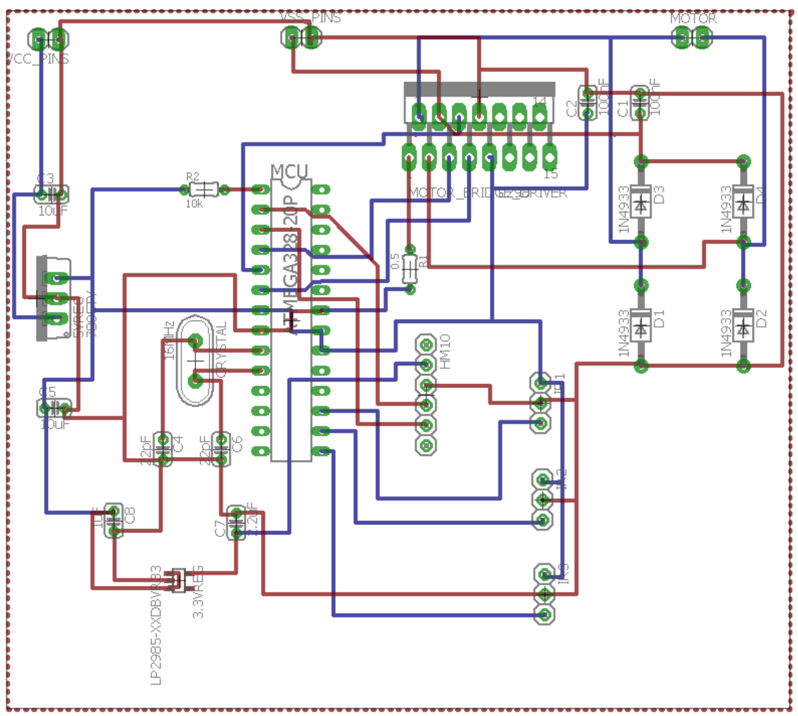

Figure 2.2: Speed Control PCB

2.3.1 Microcontroller

An ATmega328 was used as the microcontroller for this unit. The microcontroller communicates with the IR sensors of the speed detection unit (placed along the track) and the Bluetooth receiver.

The IR sensors are placed on speed limit signs around the track. When the train passes by the sign, the IR sensor detects the IR LED on the train to determine that the train has passed it. The sign then relays this information to the microcontroller and based on which pin it is communicating on, the microcontroller determines which speed limit sign the train has just passed and thus what speed it needs to adjust to. The microcontroller calculates the duty cycle for that speed and begins outputting a PWM signal to an enable input in the full-bridge driver circuit. Input pins to the full-bridge driver circuit allow the microcontroller to select which direction the train should move. For our purposes, we limited the train to forward motion only.

The Bluetooth receiver communicates with the Bluetooth transmitter of the obstacle detection unit to determine if an obstacle has been detected. When the transmitter relays that an obstacle has been detected, the Bluetooth communicates this over serial UART (universal asynchronous receiver-transmitter) to the microcontroller which changes the input pins (pins 5 and 7) of the full-bridge driver circuit to disable the bridge and thus stop the train. The delay in Bluetooth communication and UART is small enough that we can detect obstacles in time to halt motion before impact.

The combination of the input (pins 5 and 7) and enable (pin 6) pins to the L298 IC of the full-bridge driver determines whether the train brakes or if it moves and the speed/direction with which it moves. While enable is being supplied with a PWM signal, the train will move. During this, if both input pins are set high or low the train will stop. When only pin 5 is high, the train will move forward. When only pin 7 is high, the train will move backward. We disabled pin 7 from ever going high so that the train never moves backward, as we have not implemented obstacle detection in the reverse direction. While the enable pin is low the train comes to a free running motor stop which we did not utilize due to its larger stopping distance compared to braking.

The software flowchart for this microcontroller can be seen in Figure 9 of Appendix B.

2.3.2 Bluetooth Receiver

This Bluetooth module receives the 'halt' signal from the train when the obstacle detection unit detects an obstacle on the tracks. It then relays this message to the speed control microcontroller via serial UART so that it can stop the train.

We calculated the delay from various serial communications during the braking process as 17 ms (excluding a 6 ms delay from the Bluetooth). With an additional 33 ms from measuring and an overall timing budget of 100 ms in order for the train to halt within our maximum stopping distance, our Bluetooth module must have a latency of less than 50 ms. Typical Bluetooth modules have a latency of 100 ms, while Bluetooth low energy (BLE) modules have a latency of 6 ms [2]. For this reason, we selected the HM-10 BLE module for receiver and transmitter and our timing requirements were met.

2.3.3 Full-Bridge Driver Circuit

The full-bridge driver circuit consists of the L298 IC and the motor of the train, as well as some diodes and capacitors to ensure proper functioning of the full-bridge of the L298.

The L298 is a dual full-bridge driver. It contains a power supply pin rated for up to 50 V. It also has two input pins and an enable pin for controlling the motor. When the enable pin is high, the motor can receive current. Setting one of the inputs high and the other low determines if the motor operates in the forward direction or the reverse direction. When both input pins are set high or low, a fast motor stop occurs - braking the motor. When the enable pin is set low, a free running motor stop occurs.

In our design, we use one of the full-bridges of the L298. We placed a 16 V supply on the power supply pin to drive the motor. We control the enable pin with a 100 Hz bit-banged PWM output from the microcontroller to control the speed of the motor. We control the input pins from a microcontroller to set forward motion or braking of the train.

2.3.4 Train Tracks

The train tracks allow the train to run. Voltage is supplied to one rail and ground is connected to the other (there are two terminals on the side of the track to connect to). This allows current to flow through the motors on the train via the metal wheels. The train and tracks were purchased from a common model train manufacturer.

2.4 Speed Detection Unit

The speed detection unit consists of three IR sensors, each placed on a speed limit sign, and an IR LED, which is placed on the train. Each sensor is placed on a speed limit sign along the perimeter of the track. When a sensor detects IR light from the LED, the microcontroller in the speed control unit will determine which IR sensor is detecting the LED and change speed of the train by changing the duty cycle of the PWM enable signal controlling the full-bridge driver that powers the tracks.

2.4.1 Infrared LED

The IR LED is used as part of the speed limit sign detection system. The light shines continuously from its place on the outside of the train, and an IR sensor along the track only detects the signal when the train passes it. The sensors in turn send a signal to the speed control unit microcontroller to change the speed. The LED is powered with the 5 V output of the mini microcontroller of the obstacle detection unit, pulled down with resistors to provide 3 V.

2.4.2 Infrared Sensor

The IR sensor is used to detect the IR LED on the train as it passes by. Each sensor is placed on a speed limit sign. When a sensor detects the LED, it sends a signal along a wire to the speed control unit microcontroller. The microcontroller has an input pin for each of the three speed limit signs so it can easily determine which speed the train must adjust to. We constructed and placed cylindrical “blinders” on each sensor in order to limit the beam width and ensure they only detect the LED when the train is in front of them and to ensure they do not pick up any IR signals from the ToF sensors.

2.5 Obstacle Detection Unit

This unit contains two laser ToF (VL53L0X) sensors to detect obstacles ahead on the track, an Arduino Pro Mini microcontroller to process the output of the ToF sensors, and a Bluetooth transmitter to relay the stop signal back to the speed control unit.

Based on our speed and stopping distance measurements, at maximum speed the train takes about 14 cm to stop. As such we designed the detection system to be able to detect an object at least 14 cm ahead on the track. We chose to design it so that the unit can detect an object more than 14 cm ahead on the track so that any latency in communication and range measurement is accounted for as well. In our system, the obstacle detection unit is able to detect an object up to 20 cm away.

2.5.1 Microcontroller

This unit's microcontroller is located on top of the train. It receives data from the laser ToF sensors and, if an obstacle is detected, transmits a 'halt' signal to the Bluetooth module which notifies the speed control unit microcontroller to halt motion.

Refer to Figure 8 in Appendix C, page 25, for the microcontroller's software logic flowchart. The microcontroller first initializes the pins for the RF and ultrasonic transmitter and the IR LED. Other initializations include connecting the Bluetooth module and restarting the laser ToF sensors to set different addresses to distinguish between the two sensors. After the initialization, the software enters an indefinite loop. The loop begins by transmitting the RF and ultrasonic signal and the IR code. The two laser ToF sensors each take a distance measurement, and then do a logic check for whether the distance measurements of both sensors are less than 210 mm. If the condition is satisfied, then a check is done on whether the obstacle has already been seen. If the obstacle has not been seen yet, a stop signal is sent via the Bluetooth module to the speed control unit and the obstacle is marked as seen. When at least one of the laser ToF sensors detects a distance more than 210 mm and the object is marked as seen, the obstacle is considered removed from the track and a go signal is sent to the speed control unit via Bluetooth.

2.5.2 Laser Time-of-Flight Sensor

Two laser time-of-flight (VL53L0X) sensors, each with a field of view (FOV) of 25 degrees, are placed on the front of the train. The range measurement time of these sensors is typically 33 ms. One is installed at the center pointing directly ahead so that the center of its beam is always tangent to the circular train track. The other is placed at an angle of 25 degrees away from the center of the first sensor - pointing towards the center of the track. See Figure 3 for a visual of the two lasers and their FOVs with respect to the train track, created in Geogebra. The two chord lengths displayed demonstrate the maximum distance away an object can be detected on the tracks for each sensor. Thus with these sensors, we are able to see objects from about 20 cm to 56 cm ahead on the track as displayed.

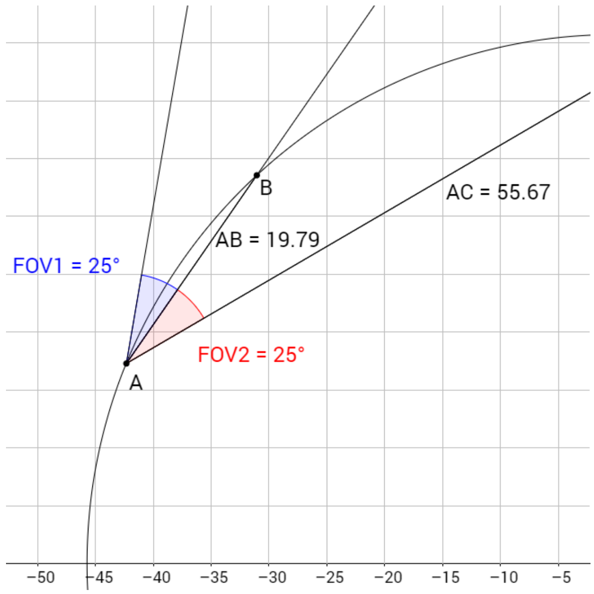

Figure 3: Two laser ToF sensor FOV on track

When both sensors detect an object 20 cm away, we will be able to determine that an object is on the track, eliminating the issue of objects near the track accidentally triggering the brake mechanism. If both sensors see an object 20 cm away, the obstacle detection unit microcontroller will determine that there is an obstacle on the track and will begin communication with the speed control unit to stop the train.

2.5.3 Bluetooth Transmitter

This component transmits the 'halt' signal to the Bluetooth receiver in the speed control unit whenever the mini microcontroller receives data of an obstacle detected on the track. The latency of this process is less than the 50 ms maximum set in our design.

2.6 Track Mapping Unit

The track mapping unit consists of one RF transmitter on the train along with one ultrasonic transmitter designed with a conical aluminum acoustic reflector on top such that it can cover 360 degrees and up to 1 m in range (see Figure 11 for the schematic). In addition, there are three ultrasonic receivers arranged outside the track which act as the centers of circles for trilateration calculations along with one RF receiver. The train unit transmits an RF and ultrasonic pulse simultaneously. The RF signals are received almost instantaneously and signal for the microcontroller to begin measuring the time it takes for the ultrasonic signal to reach each ultrasonic receiver, from which the estimated distance (radius of the circle) is calculated and used to perform trilateration to position the train.

As shown in Figure 4, the estimated position of the train is marked in red, the single intersection of all three circles.

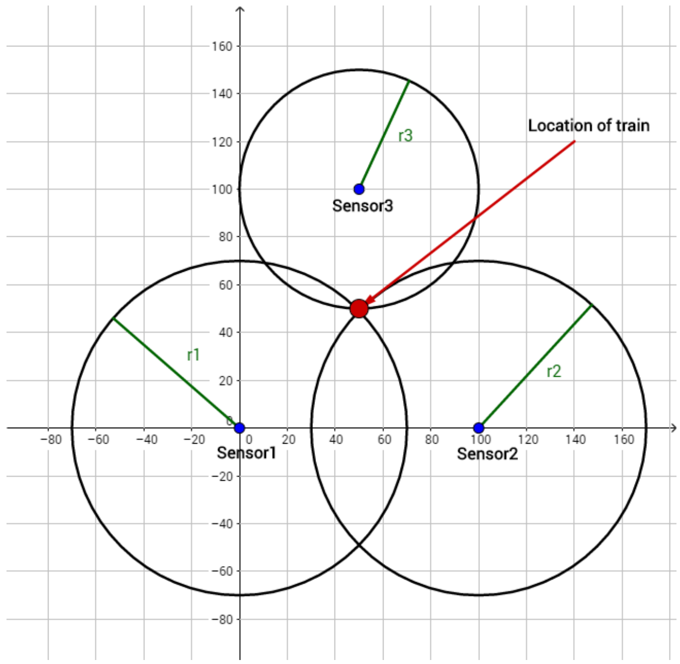

Figure 4: Trilateration

The coordinates of point B are calculated with the following formulas for the three circles, with P1 at (0, 0), P2 at (d,0), and P3 at (i,j):

$$r_1^{\,2} = x^2 + y^2 \qquad \text{(Eq. 1a)}$$

$$r_2^{\,2} = (x - d)^2 + y^2 \qquad \text{(Eq. 1b)}$$

$$r_3^{\,2} = (x - i)^2 + (y - j)^2 \qquad \text{(Eq. 1c)}$$

By solving the three equations above, we obtained the following x- and y-coordinates of the intersection of the three circles

$$x = \frac{r_1^{\,2} - r_2^{\,2} + d^2}{2d} \qquad \text{(Eq. 1d)}$$

$$y = \frac{r_1^{\,2} - r_3^{\,2} + i^2 + j^2}{2j} - \frac{i}{j}x \qquad \text{(Eq. 1e)}$$

2.6.1 Microcontroller

This unit’s microcontroller is placed on the side of the tracks. It receives an RF pulse from the RF transmitter on the train to signal the start of timing. As each of the three ultrasonic receivers detect the paired ultrasonic pulse, they communicate the reception to the microcontroller which records the time for each ultrasonic receiver. The microcontroller then uses that timing data to calculate the distance of each receiver from the train and thus position of the train via the trilateration method. A USB connection to a laptop powers this microcontroller and also allows the microcontroller to send information to display the map of the track and the train’s position on the laptop’s monitor.

Refer to Figure 7 in Appendix B on how the RF and ultrasonic receivers collect data. Essentially, the microcontroller code functions as follows. The RF receiver waits for its input to go high. Once it does, a timestamp is taken. Then, each ultrasonic receiver waits for its input to go high. After each does, a second timestamp is taken and the distance from transmitter to each receiver is calculated. The algorithm then calculates the (x,y) coordinates using Eq. 1d and Eq. 1e and sends the data over USB to the laptop.

2.6.2 Radio Frequency (RF) Transmitter and Receiver

The RF transmitter, placed on top of the train, acts as a beacon by transmitting short pulses at 434 MHz. The RF receiver detects this signal within microseconds and sends a signal to the microcontroller to begin to measure the time elapsed until the ultrasonic signal arrives as the first step in trilateration. We made a simple dipole helical wire antenna and soldered the two sides to the PCB at the receiver’s antenna and ground pins. We chose this antenna design to due to its small size and omnidirectional radiation pattern, and it served our purposes well. We found that this frequency range is noisy but assumed our requirement would still be satisfied since we only use the transmitter as a beacon. We first attempted to transmit a single digital high pulse, but realized that the noise destroyed the integrity of the whole module. Upon more research, we decided to utilize the Radiohead library [4], which sends an initialization byte, data, and a checksum. Once we implemented this library, the RF transmission worked flawlessly.

2.6.4 Ultrasonic Transmitter and Acoustic Reflector

An ultrasonic rangefinder is used as a transmitter on top of the train. To do this, we applied a logical high signal to the trigger pin and ignored the echo pin. Since the beam of the rangefinder is only 15 degrees, we requested a cone-shaped acoustic reflector from the machine shop to attach above the transmitter; that way, the sound is reflected in all directions around the track and received by each ultrasonic receiver. The sound indeed did transmit in all directions; however, we noticed degradation in accuracy with increased distance compared to the transmitter without the cone.

2.6.5 Ultrasonic Receivers

Three ultrasonic receivers are arranged outside of the track. Once the microcontroller receives the RF ‘start’ signal it begins measuring the time it takes for each ultrasonic receiver to detect the signal. Using the speed of sound, the distance from receiver to train is calculated and used to perform trilateration calculations. We also used ultrasonic rangefinders for these components and trigger them at the moment the RF signal is detected (with tape covering the transmitter) and read from the echo pin. We referenced sample code [5] for help reading from the receivers.

3. Design Verification

3.1 Power Unit

Our power unit consisted primarily of commercially-produced components, so there were not many requirements to verify. We built test circuits with the 3.3 V and 5 V regulators and probed with a multimeter to ensure we had the proper input voltage and current for the microcontrollers and Bluetooth modules. We did encounter issues with the surface-mount regulators on the on-train PCB; a few times the device seemed to overheat and ceased to function. In this case we performed extra verification to ensure there were no shorts, and restarted on a new PCB with a new component until the circuit began functioning properly. We concluded that we had a faulty regulator and met all verification parameters in the requirement and verification table (see Appendix A, page 19) with a replacement voltage regulator.

3.2 Speed Control Unit

The speed control unit was verified by using an oscilloscope to measure the circuit's output voltage, which is used to power the train tracks. When an obstacle is placed in front of the train or the input logic to the full-bridge driver is set to 00, there should be no power to the tracks (0 V measured).

The circuit behaves as expected providing the correct output to set the different speeds. Figures 5.1-5.4 show the measured voltage outputs of the speed control circuit corresponding to the different speeds.

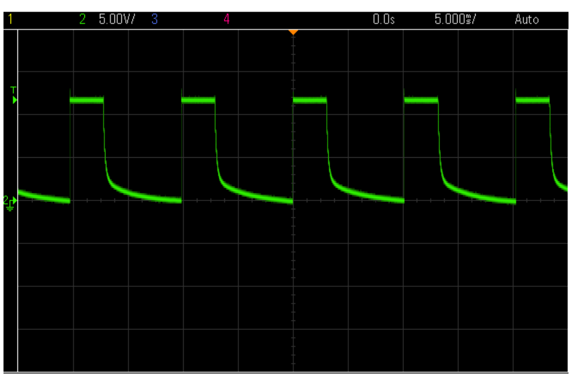

Figure 5.1: Slowest speed (30% duty cycle)

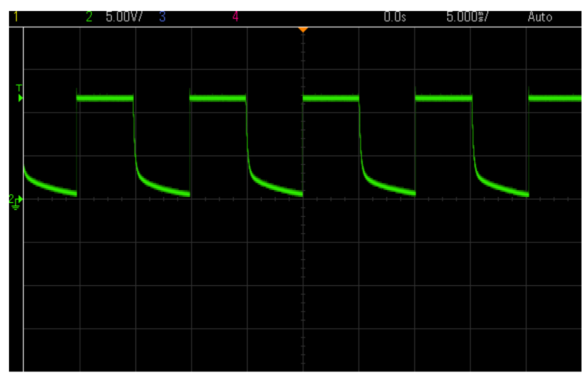

Figure 5.2: Medium speed (50% duty cycle)

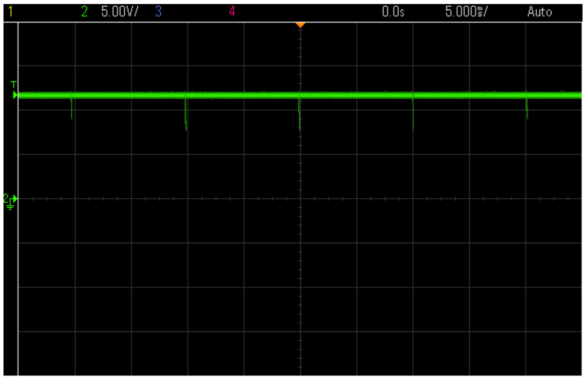

Figure 5.3: Fastest speed (100% duty cycle)

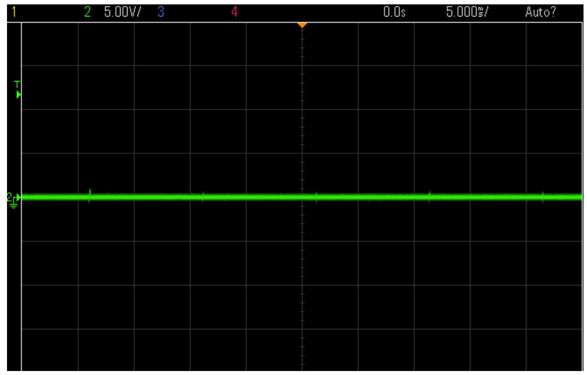

Figure 5.4: Brake (Input set to 00)

3.3 Speed Detection Unit

Speed detection is verified by moving the transmitting IR LED at varying distances and speeds and checking whether the IR sensor detects the IR signal as the LED passes it. This test is done with three IR sensors total, all waiting to read an IR signal. The speed detection unit worked independently, prior to integrating the obstacle detection unit. With the obstacle detection unit included, the IR sensors needed a cylindrical shield to avoid accidental detection of IR transmission from the ToF lasers.

3.4 Obstacle Detection Unit

The first part of the obstacle detection unit was verified by testing whether both laser ToF sensors estimated a distance less than 210 mm when an obstacle is on the track and more than 210 mm for at least one sensor when obstacle is off the track. This test was successful in classifying larger objects on the track, because the two laser ToF sensors are stacked on top of each other with a 2.7 cm separation instead of being exactly next to each other on the same horizontal plane. As a result, obstacle detection was only successful with specific obstacles that were tall enough to be detected by the upper ToF laser.

The second part of obstacle detection involved the Bluetooth communication from the obstacle detection unit to the speed control unit. The Bluetooth communication was verified by sending a ‘stop’ signal the first time the obstacle is detected and a ‘go’ signal after 1 second has elapsed since the obstacle was removed.

3.5 Track Mapping Unit

We verified the RF module fully by transmitting the message “hello” in hex and reading from the receiver. We also transmitted alternating 0 and 1 as we would need for trilateration and saw perfect accuracy.

The ultrasonic verifications proved to be less fruitful. We did successfully transmit and detect in a system with the acoustic reflector atop the transmitter and a single receiver, but accuracy decreased almost linearly with increased distance. We then placed the three receivers around the track at their pre-set coordinates and placed the transmitter atop the train and read data from the receivers that was fairly inaccurate. We believe the narrow beam angle of the receivers made it difficult to detect the train at certain points along the track. We also saw improved accuracy at slow speeds, which is due to the small train displacement during processing. We viewed the resulting map of the track on a laptop and compared it to the actual shape of the track (see Figure 6 below). While highly inaccurate, a circular formation is visible. The data points are closest to what they should be in the section of the track with a slower speed limit.

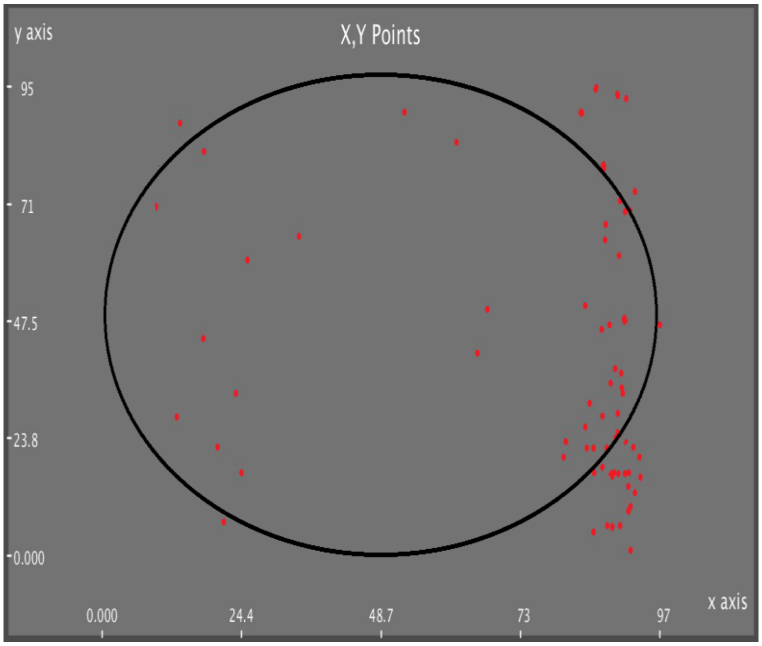

Figure 6: Track Mapping Results

4. Costs

4.1 Parts

Item	Part Number	Manufacturer	Q.	Unit Price	Cost
HO Train Set	00692	Bachmann	1	$79.99	$79.99
ATmega328P (x3)	Atmega328p-pu Chip w/ Arduino UNO Bootloader	Atmel	1	$13.47	$13.47
Arduino Pro Mini - 5V/16MHz	DEV-11113	Sparkfun	1	$9.95	$9.95
FTDI Basic Breakout	DEV-09716	Sparkfun	1	$14.95	$14.95
Bluetooth LE Module	HM-10	Qunqi	2	$14.99	$29.98
IR Sensor	TSOP38238	Vishay Semiconductors	3	$1.95	$5.85
IR LED	ILED-8	Ledtech	1	$0.25	$0.25
RF Transmitter	RF Link Transmitter - 434MHz	Wenshing	1	$3.95	$3.95
RF Receiver	RF Link Receiver 434MHz	Wenshing	1	$4.95	$4.95
Ultrasonic Rangefinder (x5)	HC-SR04	Elegoo	1	$9.99	$9.99
Laser ToF Sensor	VL53L0X	Adafruit	2	$14.95	$29.90
Full-Bridge Driver	L298N	STMicroelectronics	1	$2.95	$2.95
5V Voltage Regulator	Standard Regulator 5 Volt	Texas Instruments	1	$0.29	$0.29
3.3V Voltage Regulator	Low Drop Out (LDO) Regulator Position 3.3 Volt	Texas Instruments	2	$0.55	$1.10
Diode	1N4933	Vishay Semiconductor Diodes Division	4	$0.26	$1.04
Crystal Oscillators(x10)	HC-49S	Uxcell	1	$4.64	$4.64
PCBs		PCBway	3	$10	$30
Total					**$243.25**

4.2 Labor

Name	Hourly Rate	Total Hours	Total = Hourly Rate x 2.5 x Total Hours
Emily Alessio	$30.00	175	$13,125
Quinn Lertratanakul	$30.00	175	$13,125
John Ryan	$30.00	175	$13,125
Total		525	$39,375

4.3 Total Cost

Parts Subtotal	Labor Subtotal	Grand Total
$243.25	$39,375	$39,618.25

5. Conclusion

5.1 Accomplishments

In the span of one semester, we successfully fulfilled two of the three high-level requirements: obstacle detection and speed control. The third requirement, track mapping, functioned but was highly inaccurate.

The obstacle detection feature was functional for obstacles taller than 3 cm, and the speed control unit is able to stop the train to avoid collisions into obstacles 20 cm away. In addition, the speed control feature can adjust the train to run at three different speeds by changing the PWM duty cycle when the train passes the corresponding "speed sign" IR sensor.

For the track mapping requirement, the RF and ultrasonic communication functioned for trilateration to be calculated, but the ultrasonic communication could be improved. Overall, we presented a holistically functional project at the final demonstration.

5.2 Uncertainties

We were unable to map out the train track to best fit the shape of a circle. The problem lies with the timing between receiving the RF and ultrasonic signal. The probable cause of this problem is objects in the clear path of the ultrasonic waves, which cause the waves to bounce in other directions. Additionally, the low FOV of the receivers limit accuracy as the train moves along the track.

5.3 Ethics and Safety

One safety concern in this project is the use of alkaline batteries. These common, household batteries are relatively safe, but pose the risk of leaking acidic liquids, gels or pastes [6]. This risk is increased under high temperatures or pressure, so we ensured that the batteries remained at a temperature less than 50 degrees Celsius and placed no objects on top of them. We also checked for leaks at the beginning of every development session and did not encounter any leaks. The laser rangefinder did not pose a safety risk since it is a Class 1 laser. As members of the IEEE community, we "accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment" [7].

Since the time frame of the project is short, we faced obstacles that hindered our progress. Regardless of such obstacles, we abide "to be honest and realistic in stating claims or estimates based on available data" and "to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others" [7]. In return for the help from our classmates, teaching assistants, and professors, we tried to "assist colleagues and co-workers in their professional development" and "support them in following [the IEEE Code of Ethics]" [7].

This toy train project did not pose any other ethical concerns, because the final product is simply a hobbyist toy. The scale of this project is too small to consider applications in larger fields, in which there would be moral dilemmas that arise from a toy enjoyed by many individuals around the world.

5.4 Future Work

In the future, we would like to improve our project in both technical and aesthetic aspects. On the technical side, we want to improve the track mapping accuracy and be able to detect obstacles of varying heights. For the aesthetic improvements, we plan to redesign the layouts of our PCBs, provide encasings for the PCBs, and hide a majority of the exposed wires and circuit boards.

The track mapping accuracy can be improved by upgrading the ultrasonic transmitters and receivers to transmit cleaner signals and have less sensitivity to noise. Another possible improvement, with the existing hardware, would be to move the ultrasonic receivers further away from the track to avoid sound bouncing off each receiver and to increase the elapsed time to reduce rounding errors.

For the obstacle detection height, a PCB would be designed to house both VL53L0X sensors next to each other in the center of the board, with the supporting components (i.e. pull-up resistors and capacitors) around the sensors. As a result, the two sensors would both be able to detect an object at the same height. By combining two laser ToF sensors to one board, we also reduce the number of wires needed to connect the power and signals to the laser PCB from the on-train PCB.

The layouts of the PCBs can be improved by combining the two off-track PCBs into one main PCB and reducing the spacing between components on the on-train PCB for it to better fit in a train car. By combining the two off-train PCBs, the Bluetooth communication can be omitted to send the stop signal to the speed controller and replaced with the preexisting RF communication used in track mapping. This will help with the reducing size of the on-train PCB. The on-train PCB will also utilize an ATmega328P chip instead of the full Arduino Pro Mini to reduce space and provide more reliable power to the other components.

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Appendix A. Requirement and Verification Table

Table 1: Requirements and Verifications

Requirement	Verification	Verification Status (Y or N)
Power Unit [Total Points: 3]		
Voltage Regulator (5 V) [1.5 points] 1. The output of each voltage regulator must provide 20 mA at 5 V +/- 0.4 V to each microcontroller.	1. Probe the voltage between the VCC and GND pin of the microcontroller on the PCBs. Verify that the voltage regulated for the microcontroller is within 5 V +/- 0.4 V.	Y
Voltage Regulator (3.3 V) [1.5 points] 1. The output of the voltage regulator must provide 50 mA at 3.3 V +/- 0.4 V to the Bluetooth modules.	1. Break circuit at the Bluetooth module on the PCB to measure the voltage across its terminals with a voltmeter. Verify that the voltage regulated for the Bluetooth module is within 3.3 V +/- 0.4 V.	Y
Speed Control Unit [Total Points: 12]		
Microcontroller [2 points] 1. Relay data from the Bluetooth module at 9600 baud.	1. Start a timer and send 50 packets to the Bluetooth module. Stop the timer when all 50 packets are sent back in response from the Bluetooth module. Divide the time in half and divide 50*number of bits per packet by the halved time.	Y
Full-Bridge Driver Circuit [10 points] 1. Upon obstacle detection, the train should brake by supplying 0V to the tracks.	1. Verification process for Item 1: a. Use an oscilloscope to measure the voltage applied to the train tracks. b. Begin powering the train at any duty cycle. c. Place an obstacle on the tracks. If the obstacle detection unit is not yet verified, manually set the input pins of the driver to 00 or 11 to brake.	Y

2. When the speed limit sign senses the train passing, the full-bridge driver should alter the duty cycle to the pre-measured duty cycle corresponding to that sign's speed so that the train travels at the given speed of the sign.	d. Check that the train brakes properly by measuring 0 V across the tracks. 2. Verification process for Item 2: a. Use an oscilloscope to measure the voltage applied to the train tracks. b. Begin running the train at a 100% duty cycle. c. Time how long the train takes to traverse 1 circumference of the track. Divide the circumference (287 cm) by the measured time to get the speed. d. Place a speed limit sign near the track. e. After the train passes the speed limit sign or after changing the duty cycle, confirm that the voltage signal on the oscilloscope has changed its duty cycle. f. Repeat step 2c-e for the two other speed signs. This time the speed should be near the speed corresponding to that speed limit sign. g. Repeat process 49 times. The proper speed should be met 49 out of 50 times.	
Speed Detection Unit [Total Points: 5]		
IR LED and IR Sensors [5 points] 1. Each sensor must detect the IR LED on the train passing by with 98% accuracy.	1. Drive the train by each sensor 50 times and verify that the sensor outputs changes at least 49 times.	Y
Obstacle Detection Unit [Total Points: 20]		
Microcontroller [5 points] 1. Classify the obstacle as on/off the track with 98% accuracy.	1. Place obstacles in the FOV of one laser ToF sensor and out of the FOV of the other laser ToF sensor. Check if the microcontroller correctly classified the situation as obstacle detected or not detected. Repeat 50 times and verify that the	Y

2. Relay data to the Bluetooth module at 9600 baud.	microcontroller classifies correctly at least 49 times. 2. Start a timer and send 50 packets to the Bluetooth module. Stop the timer when all 50 packets are sent back in response from the Bluetooth module. Divide the time in half and divide 50*number of bits per packet by the halved time.	
Laser ToF Rangefinder [10 points] 1. Must have a FOV of at least 25º (at an absolute minimum, must be at least 17.66º). 2. Must have a range measurement time of less than 77 ms. 3. Detect obstacles within 20 cm ahead on the track with 98% accuracy. 4. Ignore obstacles on the side of the track with 98% accuracy.	1. Verification process for Item 1: a. Place an object 1 m in directly in front of the center of the sensor, with no other objects closer to the sensor. b. Use sensor to take a measurement of the distance. c. Repeat steps 1a-b but move the object 10 cm each time in the horizontal direction only until 50 cm is reached. d. The object should no longer be detected at 50 cm. Test the object at around 46.63 cm or just below to see that it is detected. 2. Verification Process for Item 2: a. Place an object 0.5 m in front of the sensor and run for 5 seconds and collect the sensor measurements. b. Move the object away after 5 seconds and disable data collection. c. Check to see that there are at least 64 measurements of 0.5 m. d. Repeat 49 times and ensure this is met 49 out of 50 times. 3. Place an obstacle 20 cm in front of the train 50 times and verify that both laser ToF sensor detect the object at least 49 times. 4. Place obstacles inside and outside the track at 10, 30, 50, 70, and 90 degrees away from the train at distances of 10, 20, 30, 40, and 50 cm and ensure that at least 98 out	Y

	of 100 are ignored (not detected) by one or both of the laser ToF sensor.	
Bluetooth Module [5 points] 1. Latency must be below 50 ms; no longer than 50 ms can elapse between the obstacle detection microcontroller sending ‘halt’ and the speed control microcontroller detecting ‘halt.’	1. Verification process for Item 1: a. Connect Bluetooth module with MCU. Pair the master Bluetooth (receiver) with the slave (transmitter). b. Separate the transmitter and receiver by 1 m. c. Have the transmitter send one packet and begin timing on the MCU as it does. d. Upon reception at the receiver, have the receiver send a packet in response. e. End timing once the transmitter has received the response packet. f. Divide the round trip time by two to get the latency. g. Repeat steps 2c-f 49 times and ensure that the latency doesn’t raise above 50 ms for 49 of them.	Y
Track Mapping Unit [Total Points: 10]		
RF Transmitter and Receiver [5 points] 1. Transmit and receive signals at 434 MHz with designed antennas.	1. Verification process for Item 1: a. Attach the helical antennas to the receiver. b. Use the train microcontroller to transmit an alternating 0,1 RF signal using the the Radiohead library. c. Print the buffer from the receiver using the track-mapping microcontroller to verify the message.	Y
Ultrasonic Transmitter and Receiver [3 points] 1. The receivers must be able to detect the transmitted ultrasonic signal from 5 to 95 cm away.	1. Verification Process for Item 1: a. Transmit an ultrasonic pulse from the train microcontroller by supplying a high signal to the trigger pin for 10 us. b. Place a receiver 5cm away and	Y

	read from the echo pin to verify a high signal (the detection of the transmitted pulse). Repeat at 5 cm increments. c. Repeat for the other two ultrasonic receivers.	
Trilateration [2 points] 1. Combine RF and ultrasonic signals to calculate the position of the stationary train at any point in the coordinate plane within 7.5 cm.	1. Verification Process for Item 1: a. Place the train at a point on the coordinate plane and the receivers at the pre-defined locations. b. Transmit an RF and ultrasonic pulse simultaneously from the train microcontroller c. Begin three ultrasonic timers once the RF signal is received on the track-mapping microcontroller. d. End each of the timers when the corresponding ultrasonic signal is received. e. Use the program to calculate and view the measured coordinate. Compare to the physical coordinate. f. Repeat for 11 other locations, 3 in each region of the plane.	Y

Verification Points: 50/50

Appendix B. Software Flowcharts

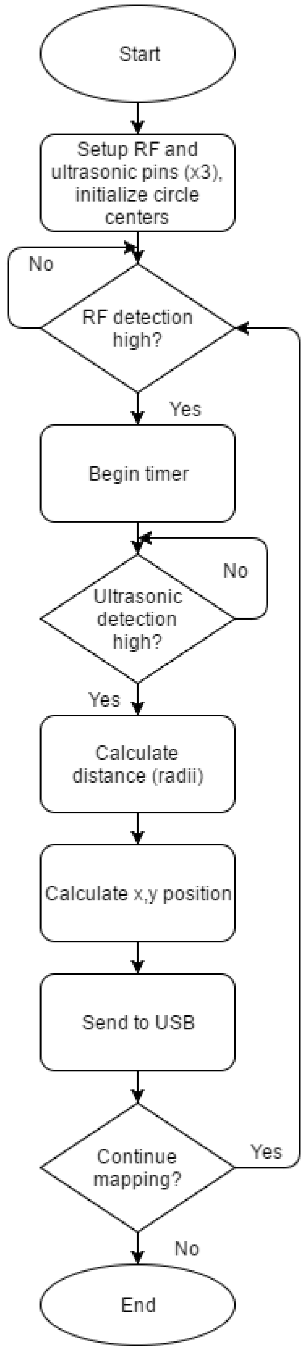

Figure 7: Flowchart for track-mapping microcontroller

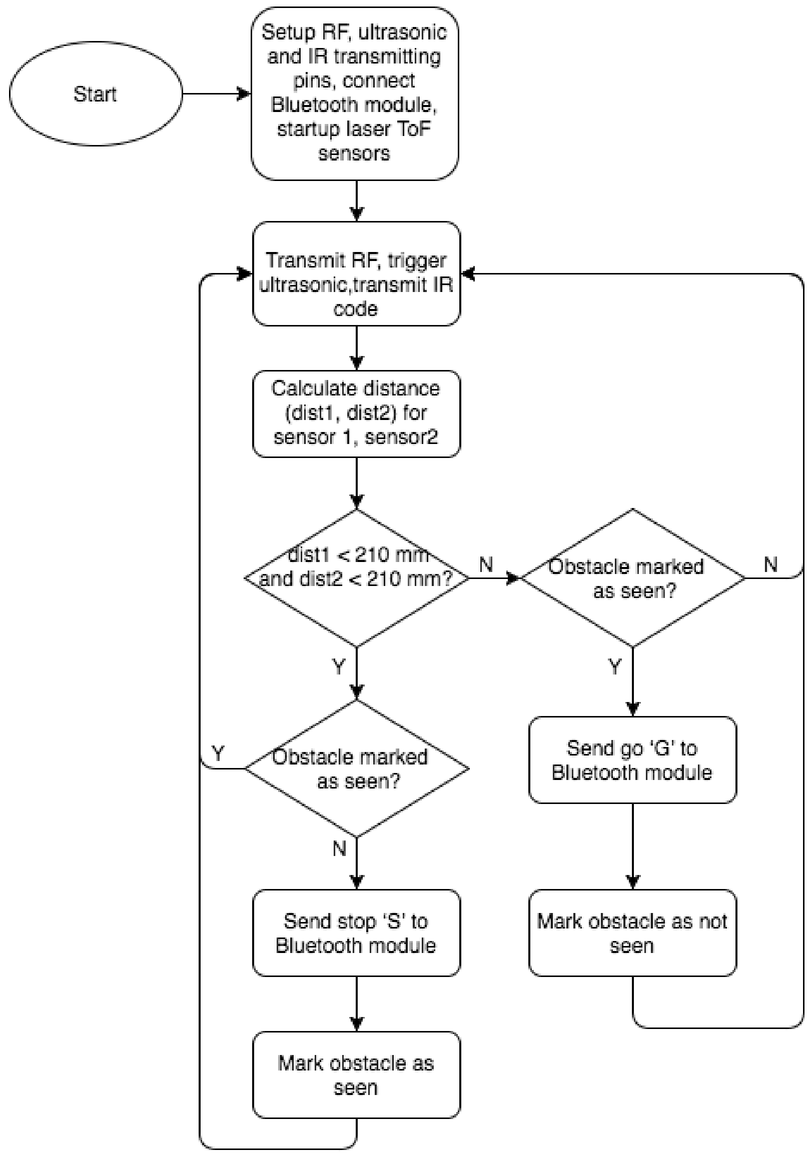

Figure 8: Flowchart for On-Train Microcontroller

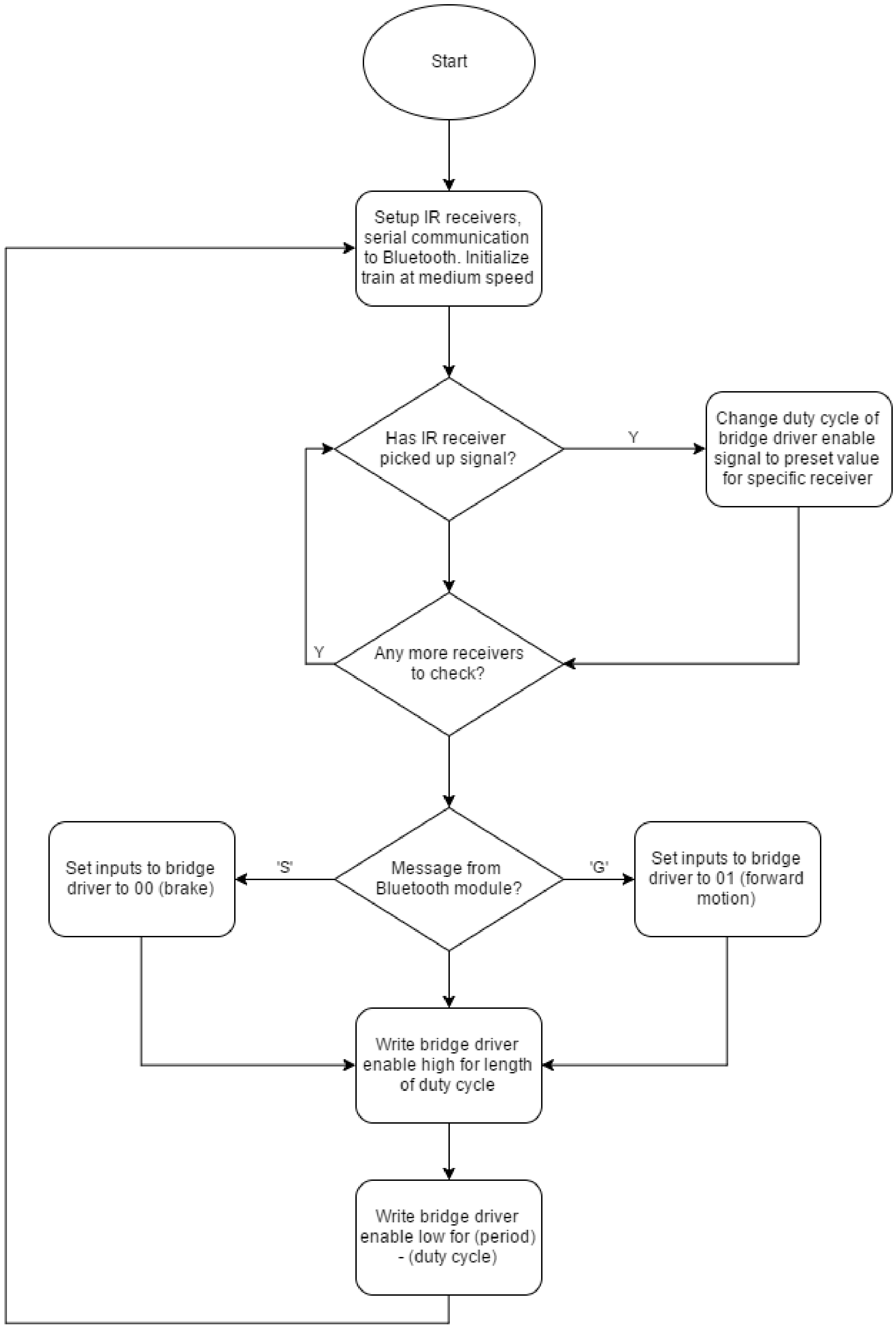

Figure 9: Flowchart for speed-control microcontroller

Appendix C. Additional Schematic and Printed Circuit Board (PCB)

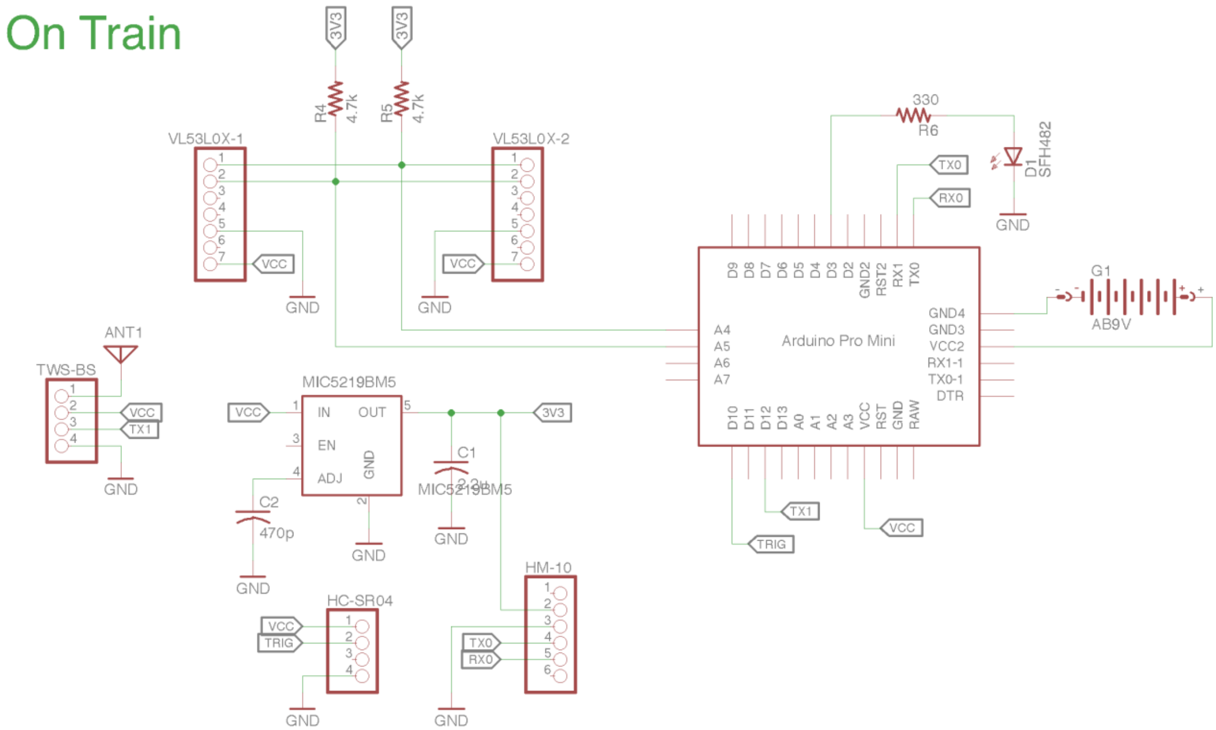

Figure 10.1: On-Train Schematic

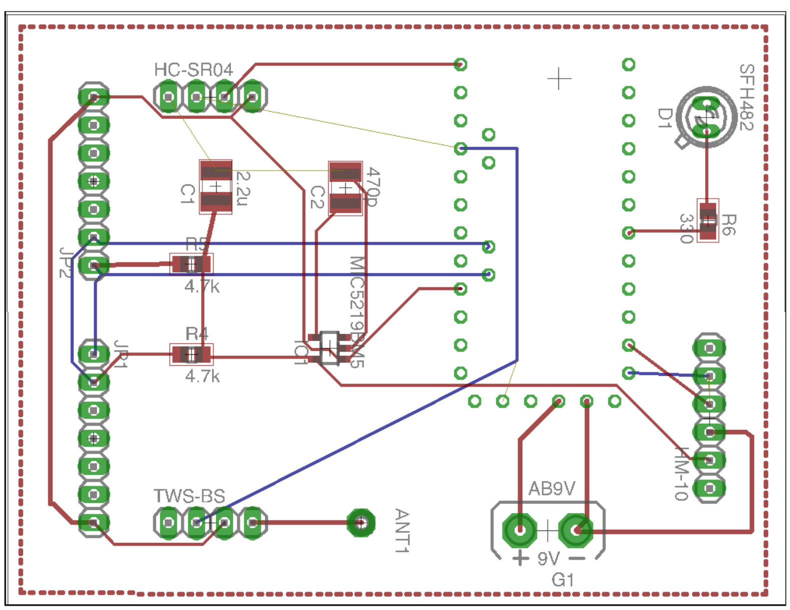

Figure 10.2: On-Train PCB

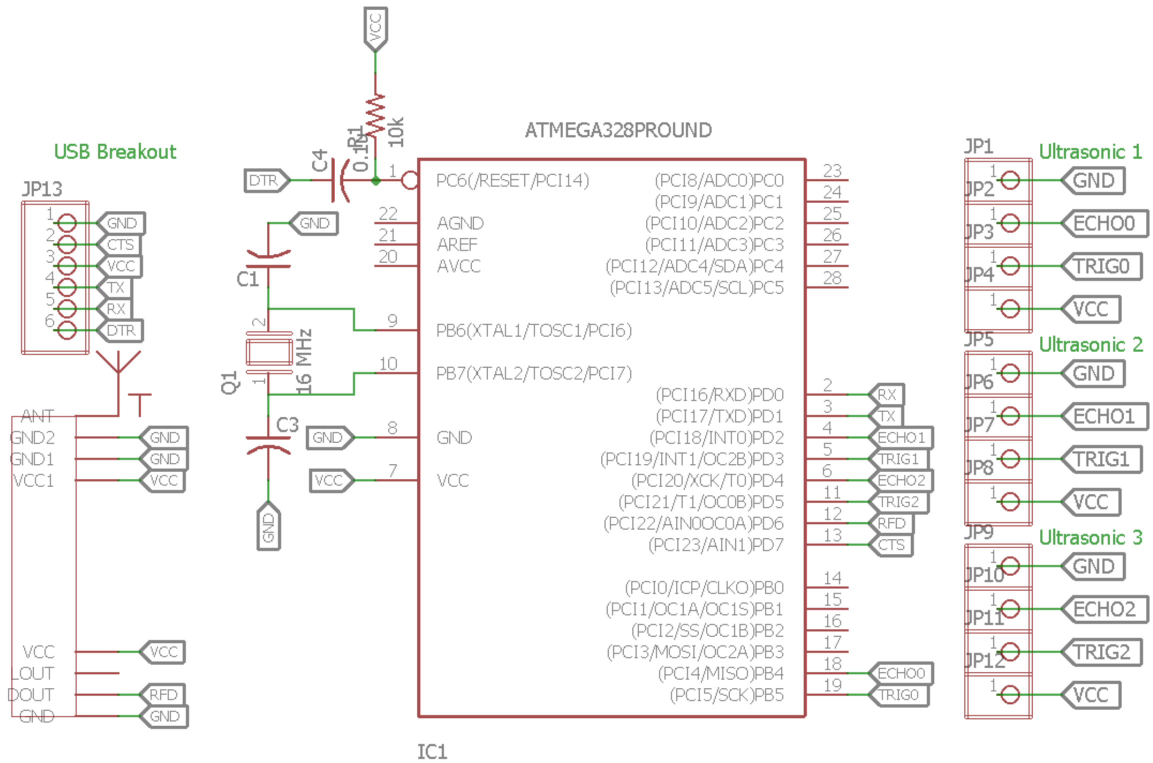

Figure 11.1: Track Mapping Schematic

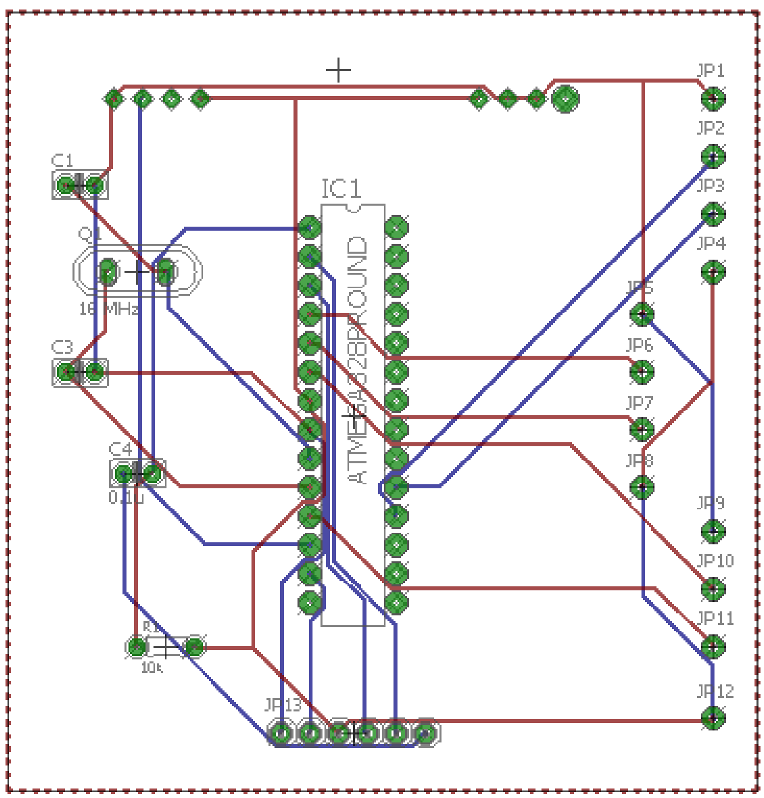

Figure 11.2: Track Mapping PCB

Appendix D. Physical Design

The physical diagram of the train system includes the train engine (excluding attachable cars) and tracks, along with the five units listed in the block diagram as shown in Figure 12.

The train carries a PCB, which connects a mini microcontroller, Bluetooth transmitter and two laser ToF sensors for obstacle detection, and IR LED for speed detection. The two laser ToF sensors are placed in front of the train at different angles to see the full range of what is on and off the track. The IR LED is placed on the outside of the train so that it can be detected by the IR sensors on the speed limit signs placed around the track.

The speed limit signs are placed along the outside perimeter of the track. These connect to the speed control microcontroller to communicate what speed limit the train has seen.

Three ultrasonic receivers are placed in a triangular formation (for trilateration) around the tracks, along with one RF receiver. These receive the signals from the RF and ultrasonic transmitters placed on the train. The three receivers are all connected to the track mapping microcontroller that calculates and displays the map of the track.

The speed control microcontroller next to the track has a Bluetooth receiver to get stopping signals from the train when an obstacle is detected as well as connections to the speed limit signs. The microcontroller then sends the speed selection, by varying the duty cycle, to the full-bridge driver which is connected to the track's power terminals.

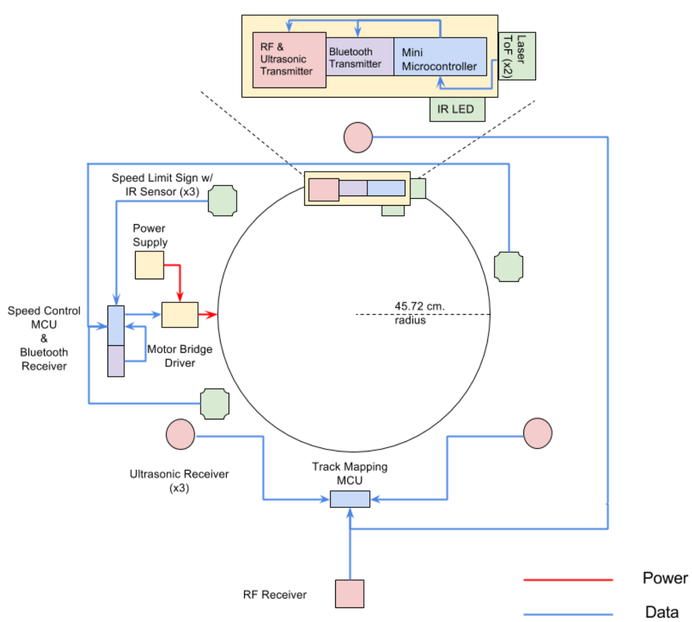

Figure 12: Physical Diagram

Appendix E. Acknowledgements

We would like to thank Professor Seth Hutchinson, Zipeng Bird Wang, Michael Fatina, and the Machine Shop staff for their assistance with our project.