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 25° (at an absolute minimum, must be at least 17.66°). 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

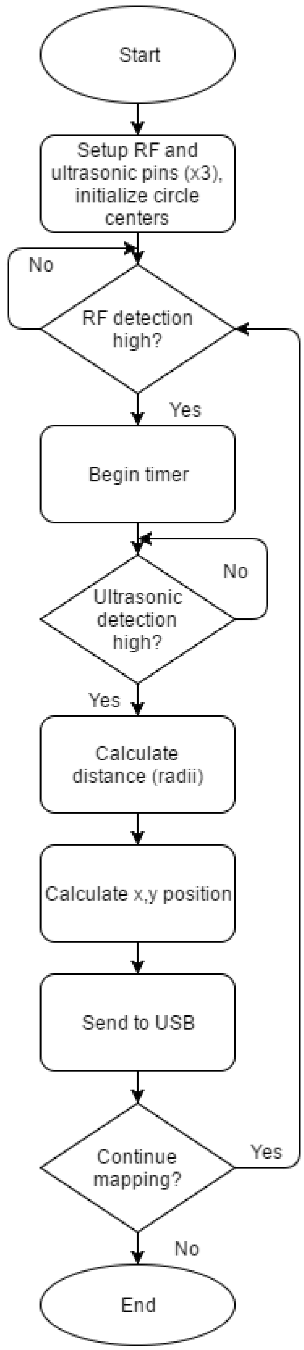

Figure 7: Flowchart for track-mapping microcontroller

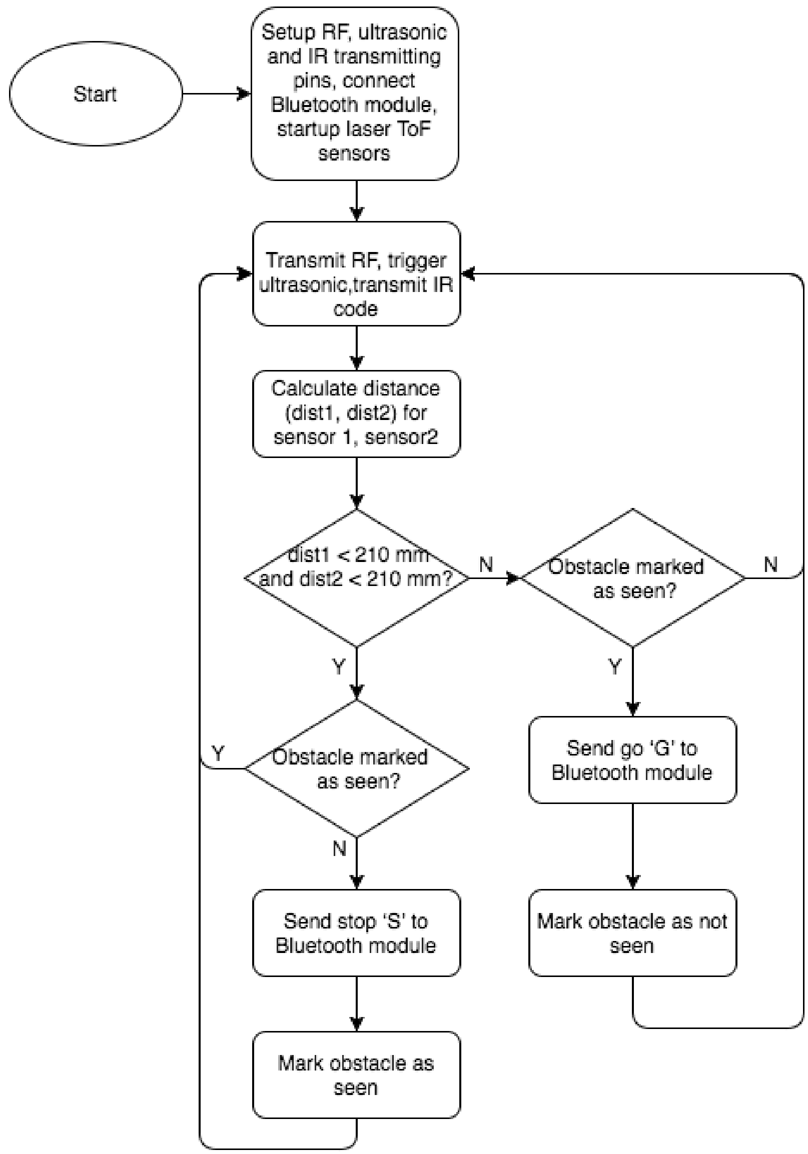

Figure 8: Flowchart for On-Train Microcontroller

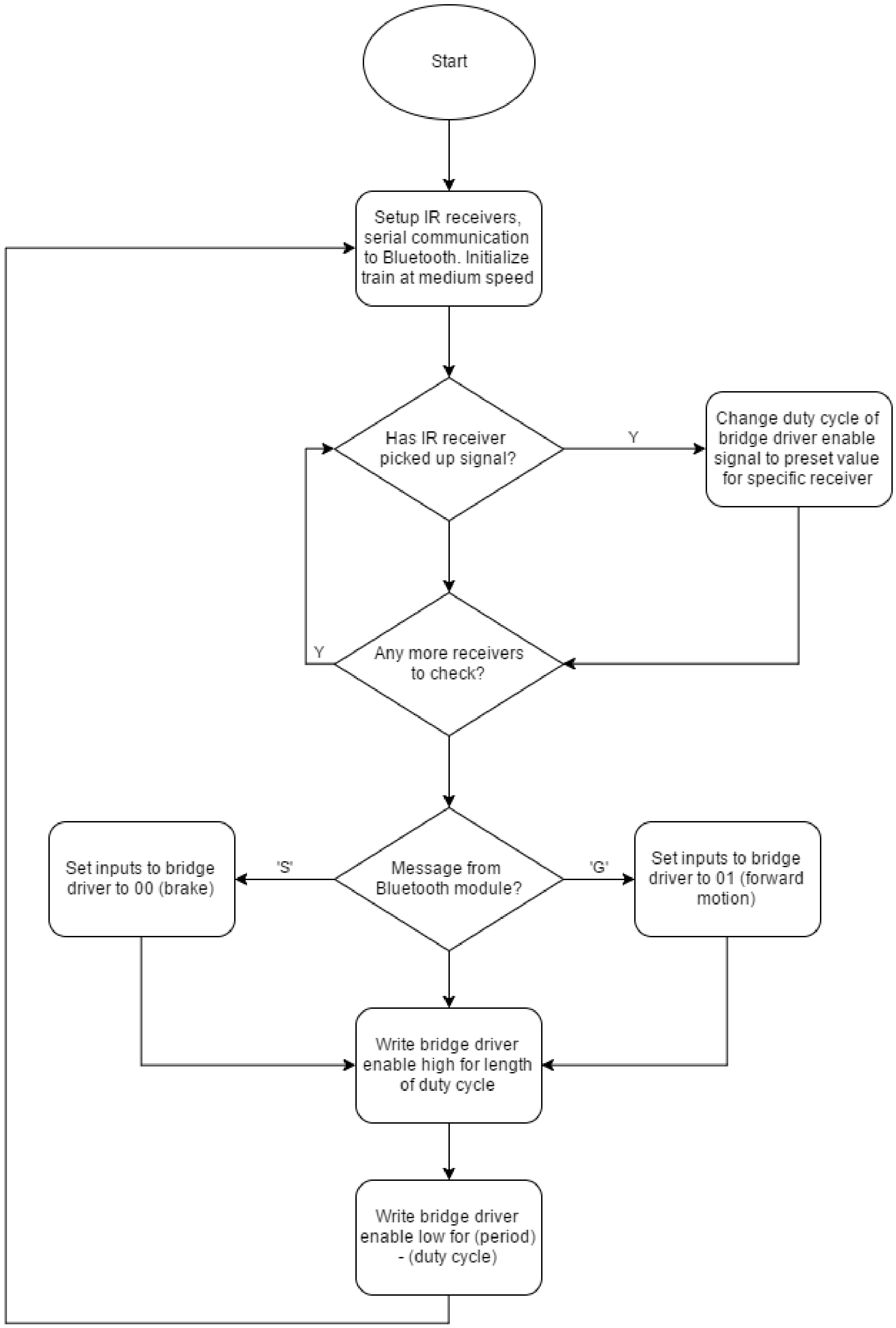

Figure 9: Flowchart for speed-control microcontroller

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

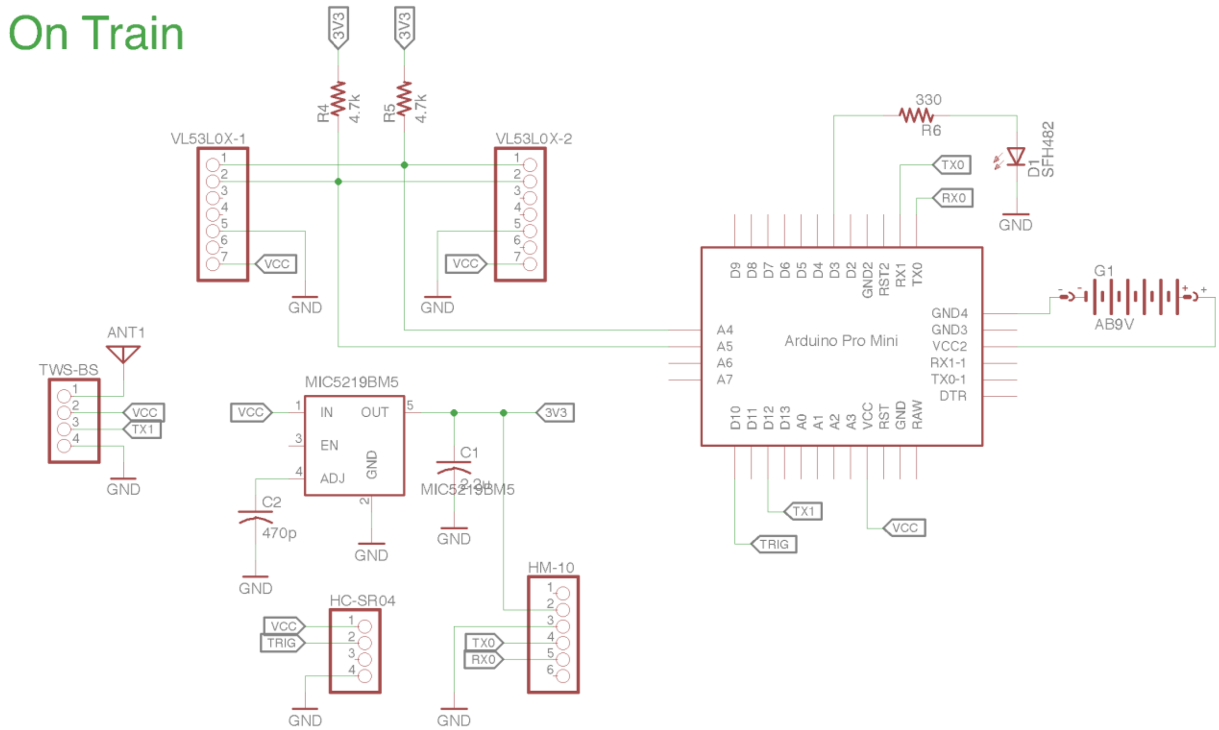

Figure 10.1: On-Train Schematic

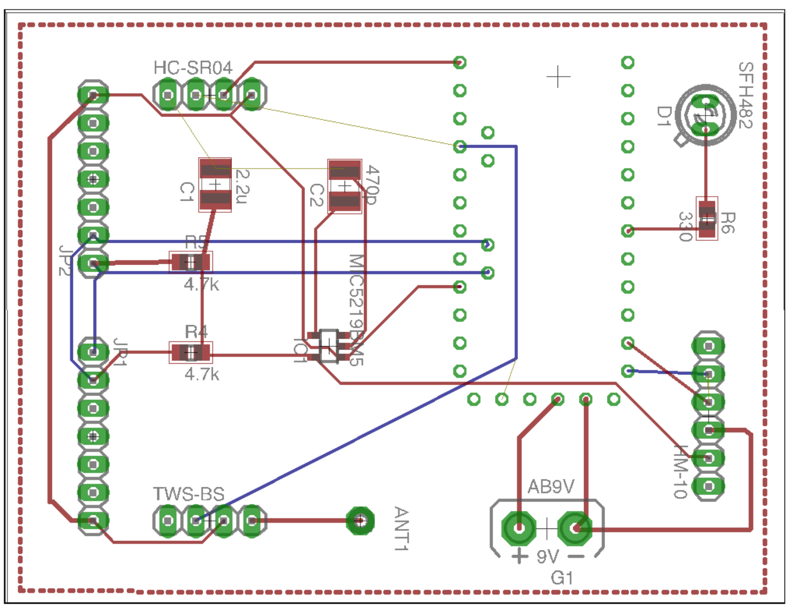

Figure 10.2: On-Train PCB

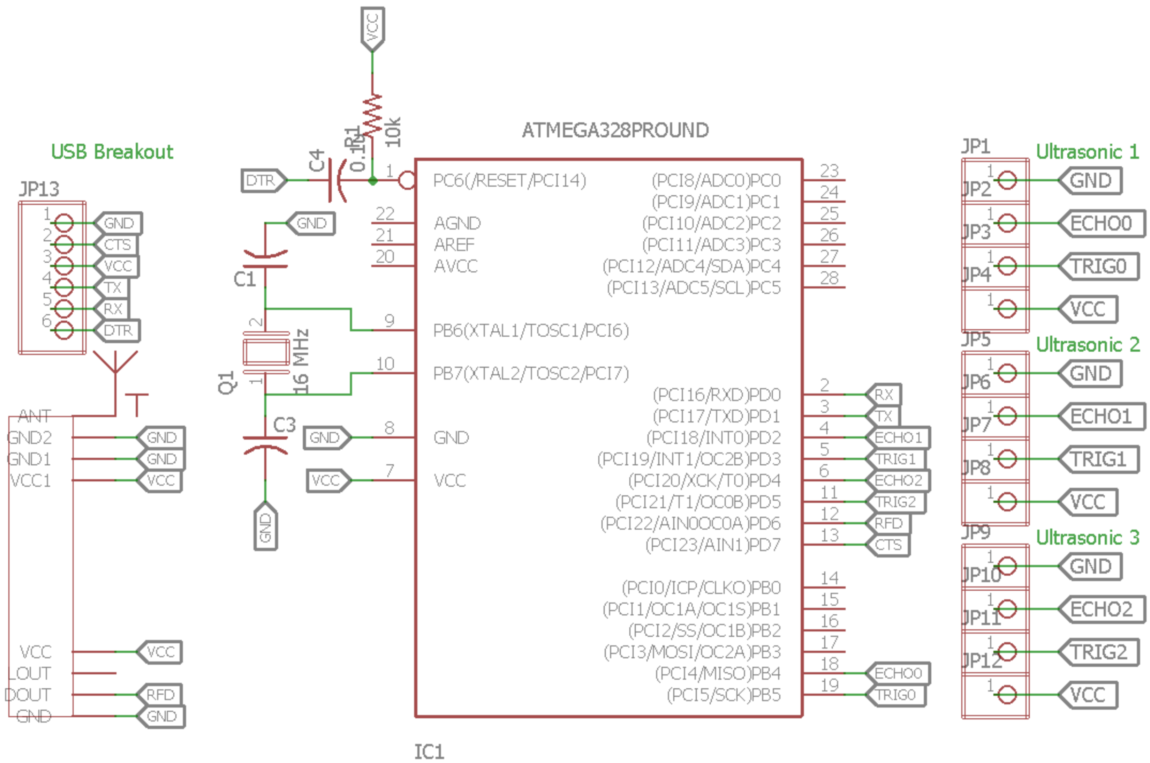

Figure 11.1: Track Mapping Schematic

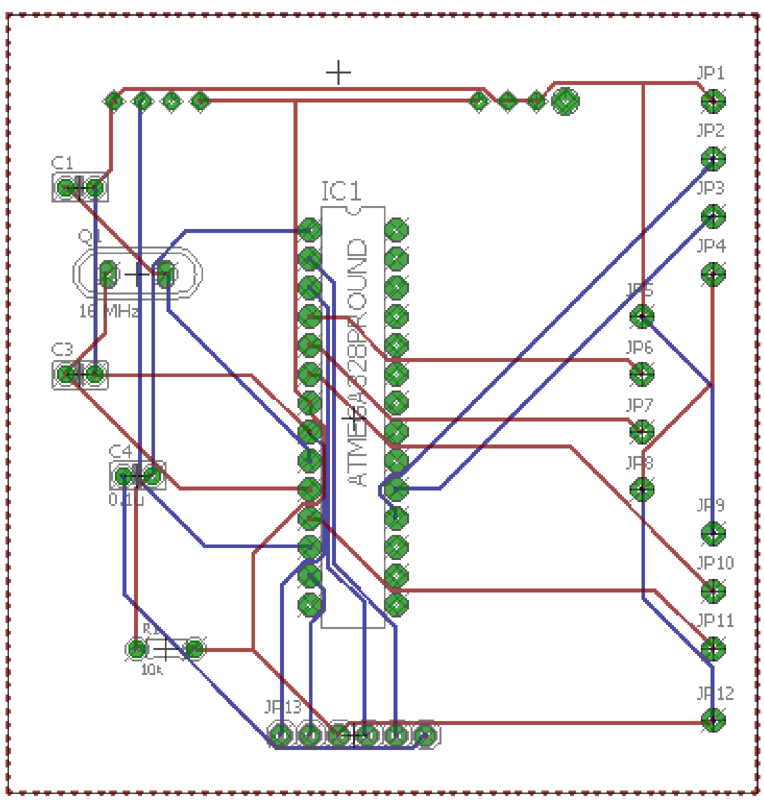

Figure 11.2: Track Mapping PCB

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.

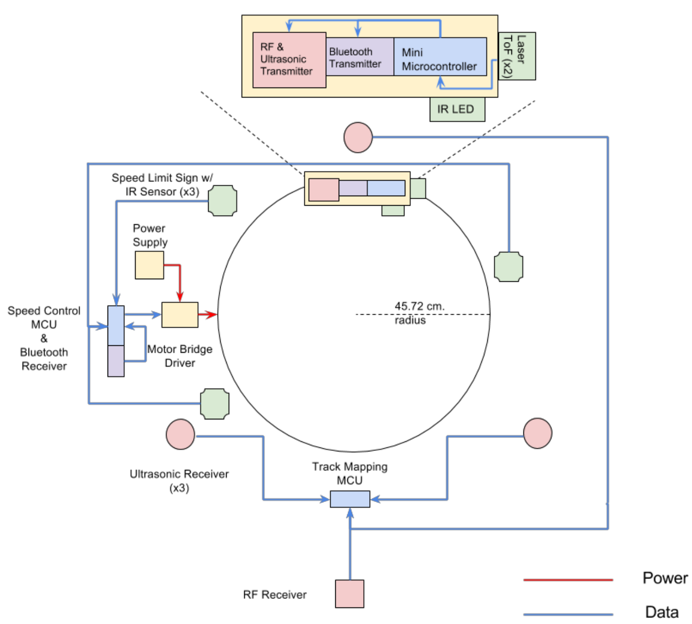

Figure 12: Physical Diagram

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.