Weld Gun Spatial Tracking System

Team 58 – Haoyong Lan, Zheyuan Hu, Xingjian Zhao
Sponsor - Illinois Tool Works Inc.
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TA: David Hanley

Abstract

Current welding training technologies are not able to track the weld gun during operation to provide feedback to welders. Our project aims to design a spatial tracking system that can track a single point on the weld gun in a 10 x 10 x 10 feet cubic space. The spatial tracking system contains one beacon and four listeners. The beacon is mounted on the weld gun and four listeners are mounted on the upper four corners of cubic space. The beacon component sends RF signal and ultrasonic sound to the four listeners components simultaneously. Then the distance between each listener and beacon is calculated based on the time difference of arrival (TDOA) between ultrasonic sound and RF signal. Distance data are sent to the host PC from master listener through Bluetooth communication. Finally, host PC calculates the 3D coordinates of the beacon point based on trilateration algorithm and displays its coordinates on the screen in real-time.

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1. Introduction

1.1. Purpose

The welding industry is expanding in the 21st century, though the number of skilled welders cannot meet the demand. According to the American Welding Society, there will be a shortage of over 200,000 skilled welder operators by 2020[1]. This is due both to a lack of incoming skilled welding operators, as well as the aging population of the current welding workforce — in the United States, the average welding operator is 57 and poised for retirement [2]. While this is not a new problem, it is an issue that many contractors, fabrication shops and manufacturing operations struggle with every day as they work to keep their operations competitive and the welding techniques are advancing [2]. New technologies and equipment that are easier to learn and use are urgently needed to recruit and train more welding operators [2].

Our project is to build a spatial tracking system to locate a single point on the weld gun in a 10 x 10 x 10 feet indoor space. The system consists of one beacon component and four listener components. The beacon is attached on the weld gun which represents the single point to be tracked. The system gathers the distances from the beacon to four listeners and computes beacon spatial coordinate using trilateration algorithm.

1.2. Functionality

The system is set up in a 10x10x10 feet indoor environment. The four listener components are mounted at the four corners of the top plane and remain stationary. The beacon component stays inside the cube, and it emits ultrasonic signal and radio frequency in each repetition. The repetition frequency is 30 Hz. Each listener component receives ultrasonic signal and radio frequency signal and measures its distance to the beacon component according to the time difference between radio frequency signal and ultrasonic signal [3].

One of the four listener component has different hardware design, and it is labeled as the master listener component. It receives distance data samples from the other three listener components. It then packs data and sends data to the host PC through Bluetooth.

The host PC (computation subsystem) reads serial distance data from four listener components through Bluetooth communication, and computes real time spatial coordinate of the beacon in MATLAB software. The requirement of beacon component location accuracy is 5 cm.

1.3 Overall Block Diagram

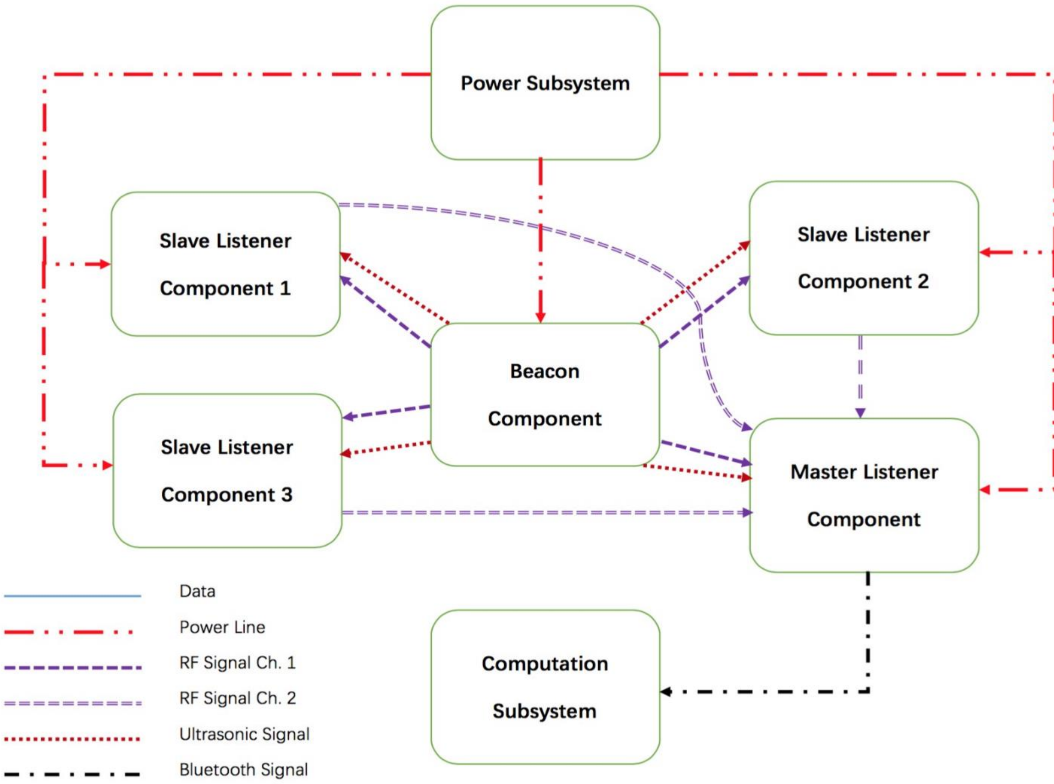

Fig 1: Overall Block Diagram

1.3. Photos of Physical Hardware

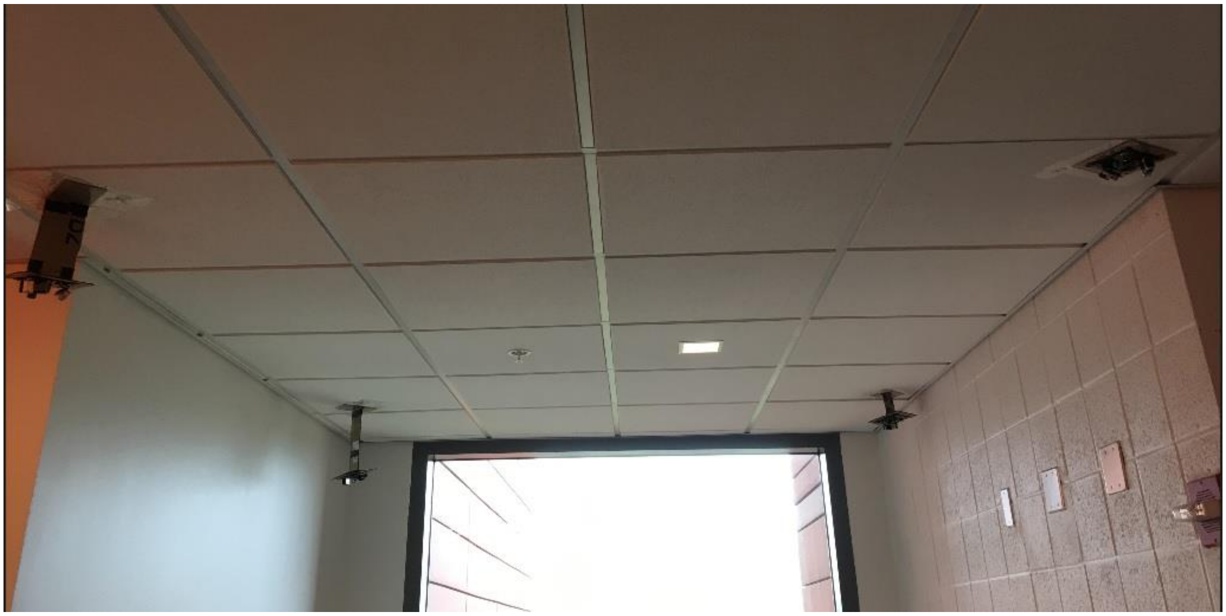

Fig 2: Image of four listener components

The four listener components are mounted on the ceiling and located in a square with side length 10 feet. They have height offsets with 0cm, 8cm, 16cm, and 24cm. The beacon component is placed inside the space, and the computation subsystem computes its spatial coordinate.

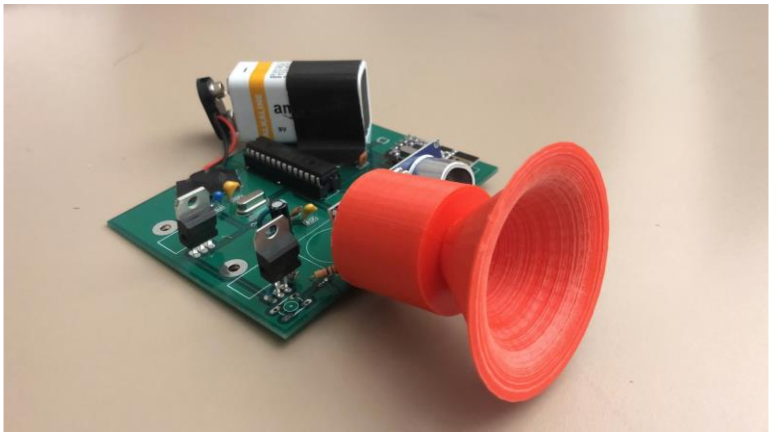

Fig 3: Image of beacon component

2. Design

2.1. Equation & Simulations

2.1.1. Distance Calculation

Ultrasonic signal and radio frequency signal are used together to measure the distance between the beacon component and the listener component. Ultrasonic signal travels around 340 m/s, while radio frequency signal travels at the speed of time [4]. Since the velocity of radio frequency signal is many orders of magnitude greater than ultrasonic signal and our measuring environment is within 10x10x10 ft cubic space, we assumed that the travel time of radio frequency signal is zero [3]. Thus, the distance equals the time difference between radio frequency signal and ultrasonic signal multiplied by velocity of ultrasonic wave (equation 3).

$$ultrasonic \qquad v_1 = 331.3 + 0.606 * T\ m/s, T\ is\ temperature\ in\ Celsius$$

Equation 1

$$radio\ frequency \quad v_2 = 3 * 10^8\ m/s$$ Equation 2

$$distance \qquad d = t * v_1$$ Equation 3

2.1.2. Three-Dimensional Trilateration Algorithm

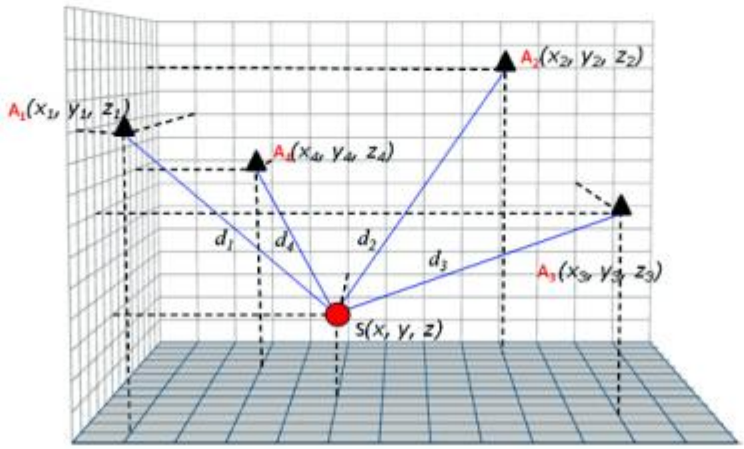

Fig 4: Trilateration in 3D [5]

As seen in Figure 4, given four listener points A1(x1, y1, z1), A2(x2, y2, z2), A3(x3, y3, z3), and A4 (x4, y4, z4). Then d1, d2, d3, d4 are distance measurements to the weld gun beacon point s(x, y, z). Then the equations for 3D trilateration are given below.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_1^2$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = d_2^2$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = d_3^2$$

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = d_4^2$$

Equation 4 [5]

Above equations can be further simplified to three system of linear equations.

$$2(x_2 - x_1)x + 2(y_2 - y_1)y + 2(z_2 - z_1)z = (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2) - (z_1^2 - z_2^2)$$

$$2(x_3 - x_1)x + 2(y_3 - y_1)y + 2(z_3 - z_1)z = (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2)$$

$$2(x_4 - x_1)x + 2(y_4 - y_1)y + 2(z_4 - z_1)z = (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2)$$

Equation 5 [5]

Finally, the x, y and z coordinates of weld gun point s can be calculated using Cramer's rule in MATLAB.

$$X = \frac{\begin{vmatrix} (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2) - (z_1^2 - z_2^2) & 2(y_2 - y_1) & 2(z_2 - z_1) \\ (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2) & 2(y_3 - y_1) & 2(z_3 - z_1) \\ (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2) & 2(y_4 - y_1) & 2(z_4 - z_1) \end{vmatrix}}{\begin{vmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & 2(z_2 - z_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) & 2(z_3 - z_1) \\ 2(x_4 - x_1) & 2(y_4 - y_1) & 2(z_4 - z_1) \end{vmatrix}}$$

$$Y = \frac{\begin{vmatrix} 2(x_2 - x_1) & (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2) - (z_1^2 - z_2^2) & 2(z_2 - z_1) \\ 2(x_3 - x_1) & (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2) & 2(z_3 - z_1) \\ 2(x_4 - x_1) & (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2) & 2(z_4 - z_1) \end{vmatrix}}{\begin{vmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & 2(z_2 - z_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) & 2(z_3 - z_1) \\ 2(x_4 - x_1) & 2(y_4 - y_1) & 2(z_4 - z_1) \end{vmatrix}}$$

$$Z = \frac{\begin{vmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & (d_1^2 - d_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2) - (z_1^2 - z_2^2) \\ 2(x_3 - x_1) & 2(y_3 - y_1) & (d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) - (z_1^2 - z_3^2) \\ 2(x_4 - x_1) & 2(y_4 - y_1) & (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2) \end{vmatrix}}{\begin{vmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) & 2(z_2 - z_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) & 2(z_3 - z_1) \\ 2(x_4 - x_1) & 2(y_4 - y_1) & 2(z_4 - z_1) \end{vmatrix}}$$

Equation 6 [5]

2.2. Design Description

2.2.1. Power Subsystem

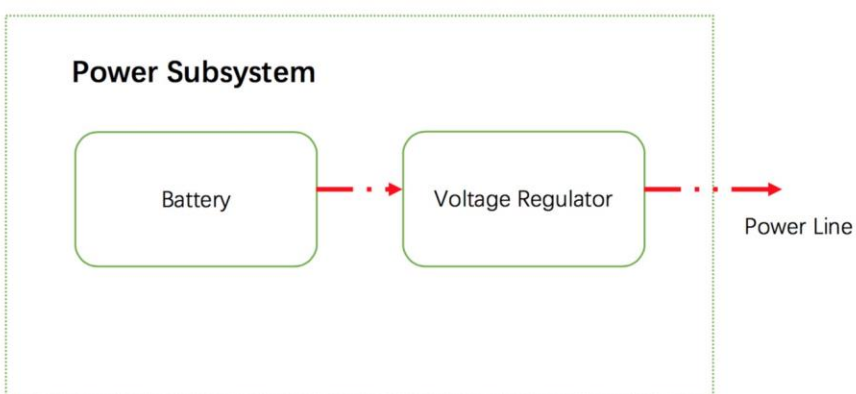

Fig 5: Power Subsystem Block Diagram

In order to power up the beacon component and every listener component, we construct individual power subsystem for each of them. The power source is 9V battery. We use voltage regulator to convert the input voltage to 3.3V and 5V outputs. To stabilize output voltage, capacitors are connected in parallel with the voltage regulator input and output pins [6][7]. 3.3V is connected to the radio frequency module, and 5V is connected to the MCU and the remaining sensors / modules.

2.2.2. Beacon Component

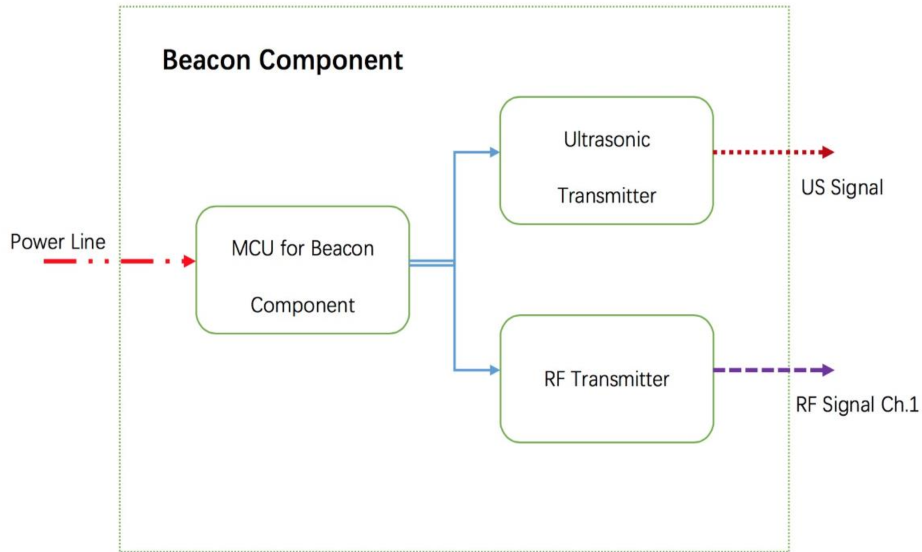

Fig 6: Beacon Component Block Diagram

Beacon component emits radio frequency signal and ultrasonic signal simultaneously at each repetition. The repetition frequency is 30 per second. The beacon component contains an MCU, an ultrasonic sensor, a radio frequency module, and the power subsystem. The transmitter of our ultrasonic module does not support enough directivity to multicast ultrasonic signal to all listener components [8]. Our solution is to design and 3D-print an acoustic horn mounting on the transmitter of the ultrasonic sensor in order to increase directivity [9].

The beacon runs 30 cycles per second, and the time period of each cycle is 33ms. At the beginning of each cycle, the MCU commands the radio frequency module and ultrasonic sensor to emit signal. It then keeps idle until the next cycle. The radio frequency module writes one byte of data during each transmission which indicates the index of the repetition in each second to the listener components.

The repetition rate of 30 cycles per second is chosen to meet our high-level requirement. Combination of radio frequency signal and ultrasonic signal is effective to measure distance between two points as shown in equation 3.

2.2.3. Slave Listener Component

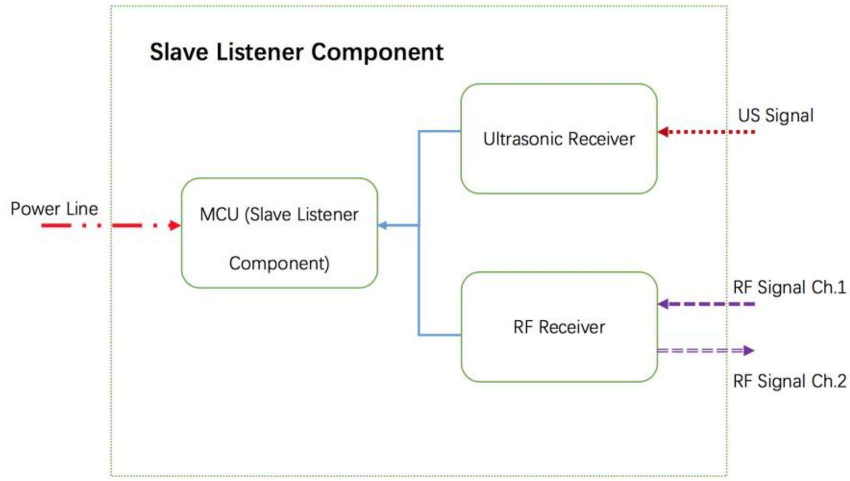

Fig 7: Slave Listener Component Block Diagram

Slave listener component contains identical hardware design as the beacon component since both ultrasonic sensor and radio frequency module can transmit / receive signal [10]. It stores the time difference between radio frequency signal and ultrasonic signal in the MCU memory. Each slave listener is selected once in different cycles per half second. When a slave listener is selected, it transmits the time difference values to the master listener using the same radio frequency module which receives radio frequency signal from the beacon.

The MCU on the listener component (both slave and master) records the timestamp when it receives radio frequency signal from the beacon. The echo pulse on the ultrasonic sensor need to rise from low to high in order to receive ultrasonic signal [8]. To do that, the MCU triggers the ultrasonic sensor. The ultrasonic sensor emitter is covered so that no actual ultrasonic signal is transmitted from the listener component. The MCU then records the timestamp when the echo pin falls from high to low indicating that ultrasonic signal is received. The time difference is then calculated and stored in memory.

The maximum payload size of radio frequency module is 32 bytes [10]. Each time difference sample is a short variable and is 2 bytes in size. Each slave listener component is selected once every half second, and it sends 15 samples of time difference data to the master listener component. Each transmission sends 30 bytes of data which is below the maximum payload size.

Fig 8: Time diagram of ultrasonic sensors

Fig 8 shows the time measurement of ultrasonic sensors in oscilloscope.

Green line represents the trigger pin on the beacon component.
Pink line represents the trigger pin on the listener component.
Yellow line represents the echo pin on the beacon component.
Blue line represents the echo pin on the listener component.

Measurement shows that radio frequency transmission causes a small delay on the listener component. Both trigger pin and echo pin on the listener component are behind the corresponding pins on the beacon component. Measurement shows that the delay is 105 microseconds, and it is consistent in each cycle.

The echo pulse (high) on the beacon component is twice as long in duration as the echo pulse on the listener component. The beacon component receives ultrasonic signal which travels in round trip, while the listener component receives ultrasonic signal which travels in single trip [3]. It proves that our distance measurement method is effective.

2.2.4 Master Listener Component

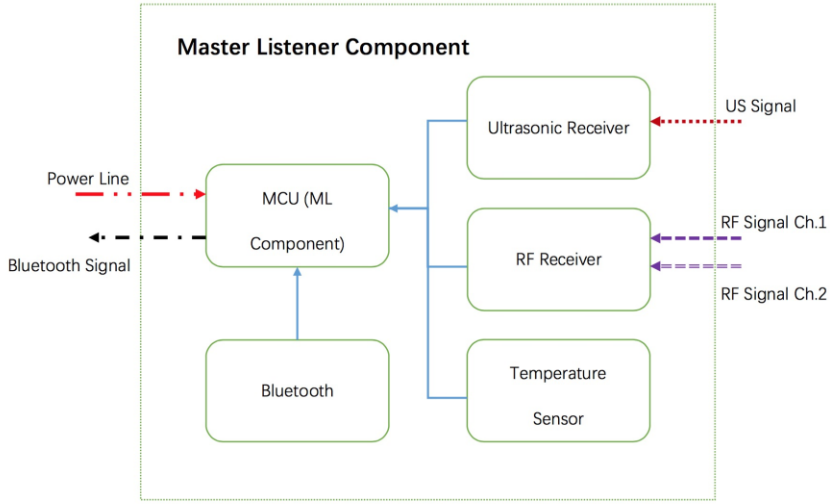

Fig 9: Master Listener Component Block Diagram

Master listener component includes all the standard functions as the slave listener component. In addition, it contains a temperature sensor and a Bluetooth module. Readings from temperature sensor are used to adjust ultrasonic wave velocity increase as temperature increases (Equation 1). The master listener component sends distance values from four listener components to PC at each repetition using Bluetooth. Bluetooth is used to communication with a host PC since Bluetooth adaptor is standard on laptops and Bluetooth is reliable for serial data transmission. The transmission rate of the Bluetooth module depends on the Baud rate of the MCU [11].

In order to recognize the source of radio frequency signal (either from the beacon or slave listener component), beacon component and slave listener components have unique write address. The radio frequency module contains a maximum of 6 pipes [10], and one pipe can be used to either read or write signal. The pipe mapping is shown in table 1. The MCU checks for pipe number during every reading operation to recognize its source.

Pipe Number	Function
0	writing
1	Reading from beacon
2	Reading from slave listener 1
3	Reading from slave listener 2

4	Reading from slave listener 3
5	unused

Table 1: Pipe Number Map

2.2.5 Computation Subsystem

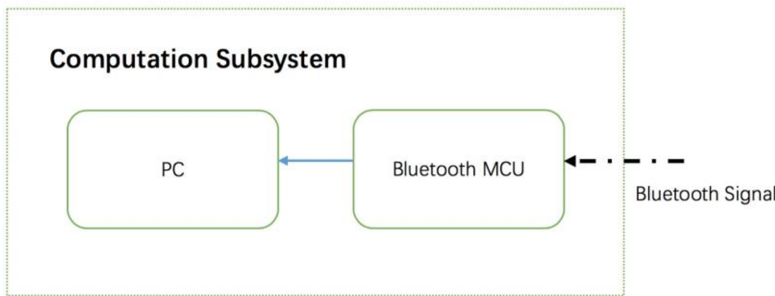

Fig 10: Computation Subsystem Block Diagram

Computation of beacon spatial coordinate is run on a laptop. The laptop contains a Bluetooth adapter which receives data from the master listener component. The software for trilateration algorithm runs in MATLAB, and it contains a graphical user interface (GUI) to display the beacon location in 3D gridded lines.

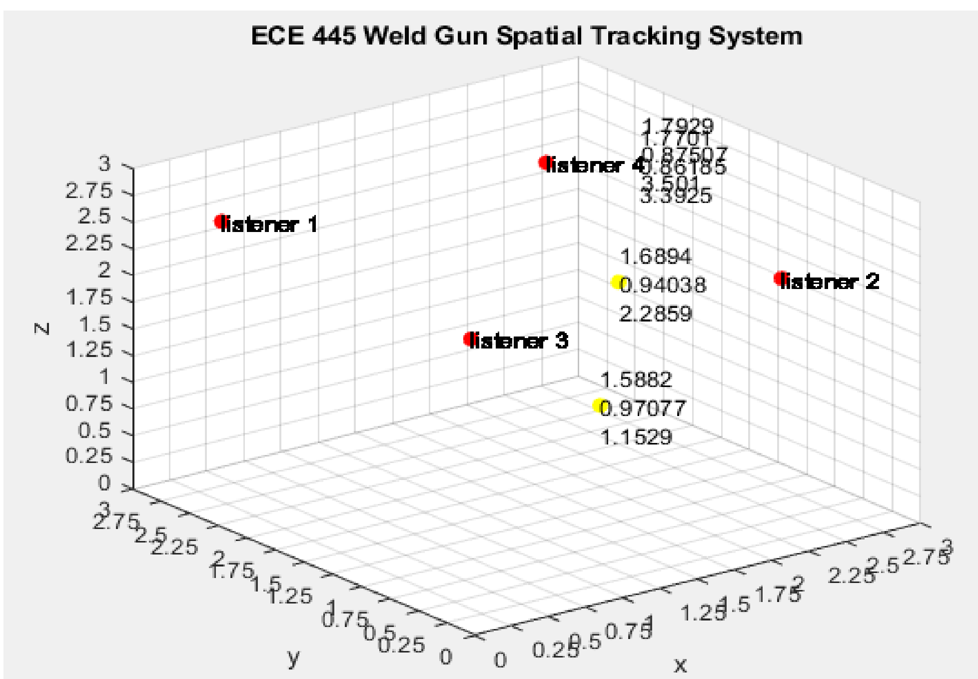

Figure 11: MATLAB GUI Test Result

Figure 11 shows the MATLAB GUI in computation subsystem. Yellow dot represents beacon coordinates and four red dots represent four respective listeners. Each axis has size of 3m which is about 10 feet. The coordinates of each listener can be manually entered by the user based on real setup environment. The reason why there are multiple beacon points is because the beacon point is computed in real-time based on real-time distance data from each listener.

2.3 Design Alternatives

2.3.1 Acoustic Horn

During our testing of beacon component, we discovered that the beam angle of ultrasonic sensors was not wide enough to ensure every listener component could receive valid signal for distance measurement. It would cause inaccurate distance measurement and even ultrasonic signal lost. According to the datasheet of ultrasonic sensor HC-SR04, the beam angle is 15 degrees. Therefore, it was necessary to find a feasible alternative to solve this problem.

Our proposed solution was to build an acoustic horn which could guide entering waves to reflect within the horn so that it would output ultrasonic waves with greater angle coverage. The horn we designed consisted of two major parts: a waveguide tube with sloped inner surface and a hollow cone [12]. We used a 3D modeling software to design the horn and printed using 3D printers. We have manufactured four different versions of acoustic horns in total. We mounted the horn on the transmitter of beacon and then measured a fixed distance of 30 cm to a listener with various angles. After primary testing, the first three versions were not well-engineered enough to produce satisfying results. The fourth horn was the horn we were using for the demo and it had been greatly enhanced performance of ultrasonic sensor from the original one. Table 2 shows the test result of the latest iteration of the horn.

Angle (Degree)	Measured Distance (cm)	Standard Deviation (cm)	Actual Distance (cm)
0	29.93	0.45	30.00
10	29.8	0.74	30.00
20	31.09	1.75	30.00
30	31.27	1.81	30.00
40	28.02	3.95	30.00
50	36.24	16.94	30.00

Table 2: Directivity and Measurement

Based on the data we collected, the ideal beam angles of this horn could achieve was around 40 degrees. When the object was deviated more than 40 degrees, the accuracy would fall beyond 5 cm which did not meet our requirements.

2.3.2 Vertical Distance Offset

When we mounted our listener components to the ceiling to test the 1st time, we found out that we could hardly obtain one beacon spatial cubic in the 10x10x10 feet space. We found out that our trilateration algorithm had difficulties to compute the height of the beacon when all listener components were installed with same height. Our simulation showed that some change in listener component height could alter the z coordinate in the computation significantly.

Thus, we attached cardboard on the back of each listener to create height difference. The four listener components vary height in 0, 8, 16, 24 cm. Our testing showed that our setup did not have significant height difference to resolve the height of the beacon component and caused inaccuracy in our results. Increasing height difference is desirable to provide better output.

3 Cost & Schedule

3.1 Parts

Part	Manufacturer	Cost / Unit	Quantity	Total Cost (Prototype)
ATMega328P	Atmel	2.20	10	22.0
HC-49S DIP 16MHz	TXC	0.454	10	4.54
HC-SR04	ElecFreaks	3.95	5	19.75
NRF24L01	Nordic	1.20	10	11.98
TMP36	Analog Devices	1.50	1	1.50

HC-06	HC	7.39	1	7.39
LD1117v33	STMicroelectronics	1.95	5	9.75
L7805	STMicroelectronics	0.95	5	4.75
9 Volt Alkaline Batteries	Amazon	1.25	8	9.99
9V Battery Clip Connector	Urbest	0.625	10	6.25
PCB	PCBway	0.5	10	5.00
Acoustic Horn	Illinois Makerlab	0.18 / gram	4	10.05

Table 3: Parts and Cost

$$Total\ Part\ Cost\ =\ \$\ 112.95$$ Equation 7

3.2 Labor

We estimate our fixed labor fee to be approximate $20/hr for each of the three members in our group and our time spent on the project will be around 12 hrs/week for the total 16 weeks of this semester. Therefore, our estimated cost of labor is shown in equation 7.

$$Total\ Labor\ Cost\ =\ 3 \times \frac{\$20}{hr} \times \frac{12hr}{week} \times 16\ weeks\ = \$11,520$$ Equation 8

3.3 Schedule

Week	Haoyong	Xingjian	Zheyuan
2/18/19	Finished Design Document and ordered components online		
2/25/19	Prepared for Design Review		
3/4/19	Tested and verified the parts we ordered; and discussed the feasibility of other similar approach		
3/11/19	Finished the PCB design of beacon component	Test for distance measurement on Arduino	Worked on the Eagle schematic and board design of Master Listener Component
3/18/19	Manufactured beacon boards	Test power subsystem circuits on breadboard	Wrote Individual Progress Report
3/25/19	Mounted beacon boards and designed trilateration algorithm	Wrote software code for beacon component	Did research on waveguide and acoustic horn; and learned how to use 3D modeling software
4/1/19	Troubleshot for potential bugs inside each beacon component and continued designing trilateration algorithm	Wrote software code for slave listener component	Designed and manufactured acoustic horns and made improvements
4/8/19	Connected Bluetooth module to MATLAB	Wrote software code for master listener component	Soldered PCBs and tested the performance of each horn
4/15/19	Tested the entire system, and made changes to create height offset		
4/22/19	Collected data, and prepared for project demonstration		
4/29/19	Prepared for the final presentation and finish writing final report		

Table 4: Schedule

4 Requirement & Verification

4.1 Power Subsystem R&V

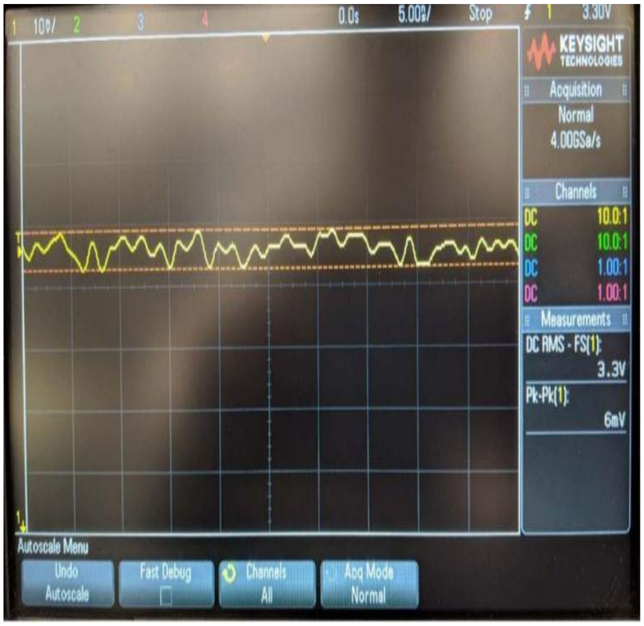

Fig 11: Voltage Measurement

We measured the power outputs on our power subsystem component using oscilloscope. As shown in Fig 11, the root mean square values are 3.3 V and 5.0V. The peak to peak is less than 10 mV in cases. Requirement are met.

4.2 Beacon Component / Listener Component R & V

We displayed the received four distance measurements on MATLAB command panel with timestamp. Results showed that MATLAB received 30 sets of distance measurement each measurement which met the requirement. We also compared the distance measurements on MATLAB and actual distance between the beacon component and each listener component. Actual distance was measured from the ultrasonic sensor emitter on the beacon component to the ultrasonic sensor receiver on the listener component using tape measures. The measured distance was within 3 cm from the actual distance most of time while there were some outliers due to ultrasonic wave reflection and beam angle limitation.

4.3 Computation Subsystem R & V

We set the beacon component stationary inside the cubic space and its spatial coordinate is (1.50, 1.00, 1.40). We collected all computed coordinate points from MATLAB in 5-

minute run. We received a sample size of 28. The trilateration computation does not generate valid point all the time due to small distance difference in height. Then we measured the average of the computed coordinate, and its value was (1.5882, 0.9708, 1.1529). The error percentage is shown in table 5.

	X direction	Y direction	Z direction
Error %	5.88	2.92	17.65

Table 5: Error rate

5 Conclusion

5.1 Accomplishments

Our final system successfully achieved most of the high-level requirements. Our weld gun spatial tracking system can track a single point on the weld gun and displays its real-time coordinate on host PC MATLAB. The main components can be easily set up in an experimental indoor space with size around 10*10*10 feet. The four listeners on the ceiling can receive both RF and ultrasonic signals with repetition rate of 30 from the beacon mounted on the weld gun. Trilateration algorithm can compute all four distance measurements data and calculate the final beacon coordinates 5 times per second. Distance from each individual listener has small fluctuations and the accuracy is within 5 cm. Although not all the beacon coordinate displayed are valid, some of them can still have an accuracy within 5 cm.

5.2 Uncertainties

We believe that ultrasonic signal from previous repetition does not vanish in our testing environment. These ultrasonic signals may bounce when encountering obstruction from walls and interference with ultrasonic signal in the current repetition. The ultrasonic sensor cannot detect whether the ultrasonic signal is from the beacon or ultrasonic signal reflected from the wall. It can cause inaccurate distance measurement and outliers were shown in our above results.

5.3 Future Work / Alternative

In order to increase the accuracy of our system, the first improvement should be creating more height difference of listeners when we set up the whole structure. The reason this will improve the accuracy is that greater height difference will help the algorithm get a better calculation result in vertical direction. We had done three trials with three different height settings; and we found

out that as the height difference increases, the result will be more precise and accurate. In addition, more listener components will enhance the accuracy of the output because more distance measurements are collected. Moreover, problems with ultrasonic sensors can be better solved if there will be more advanced sensors with less fluctuation and wider angle on the market for us to choose, or we can redesign and remanufacture the acoustic horn to make it metallic (instead of plastic) and has smoother surface (instead of rough and porous).
Since the system is built for weld gun, we can further adjust the layout of beacon component to make our system more user-friendly. For example, the size of the beacon component can be smaller by designing PCB to be double-sided so that it can better fit on the small handle of weld guns and reduce weight as well.

5.4 Ethical Considerations

We know that ethics and safety are key to the successful completion of our project and we will try our best to ensure its ethics and safety. Our project could have several potential safety issues. The power supply may get overheated and explode if the voltage is above the threshold voltage. As #1 of IEEE Code of Ethics states: "to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices and to disclose promptly factors that might endanger the public or the environment" [13]. We will connect the power unit to an oscilloscope to closely monitor the voltages of the power supply and all other units. In addition, we honestly seek and accept technical advice to keep improving our system design following #7 of IEEE Code of Ethics: "to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others" [13]. We respect the contributions of others by giving credits to works from others.

6 References

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Appendix A - Schematics

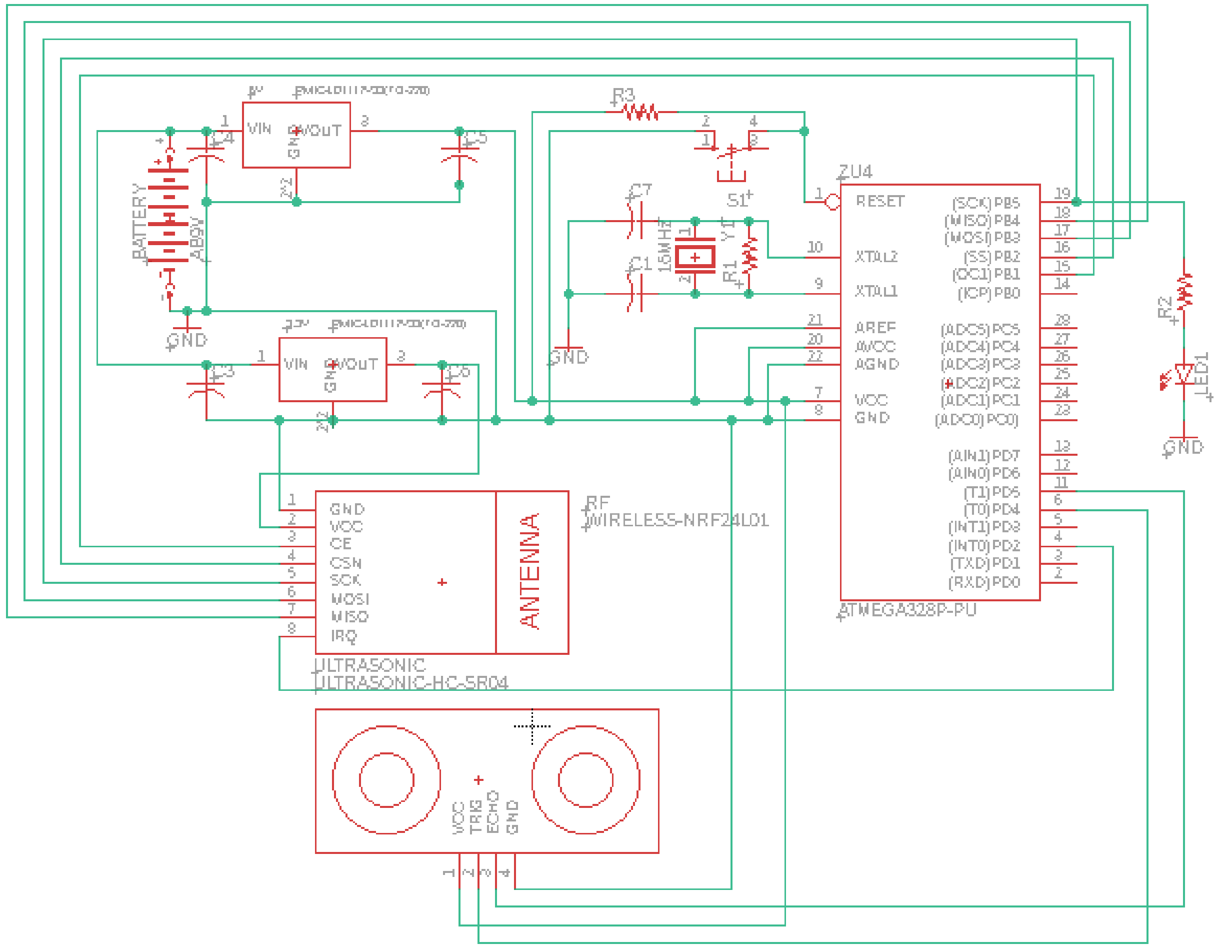

Fig 12: Schematics of beacon component / slave listener components, including power subsystem

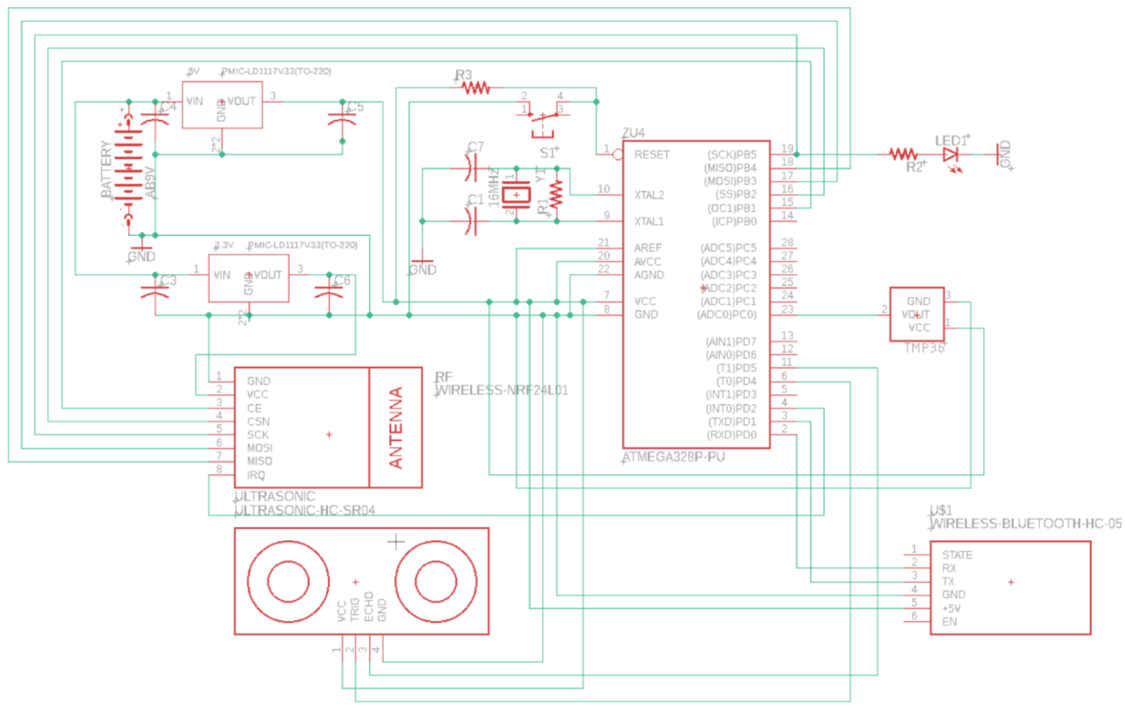

Fig 13: Schematics of master listener components including power subsystem

Appendix B - Software Flow Chart

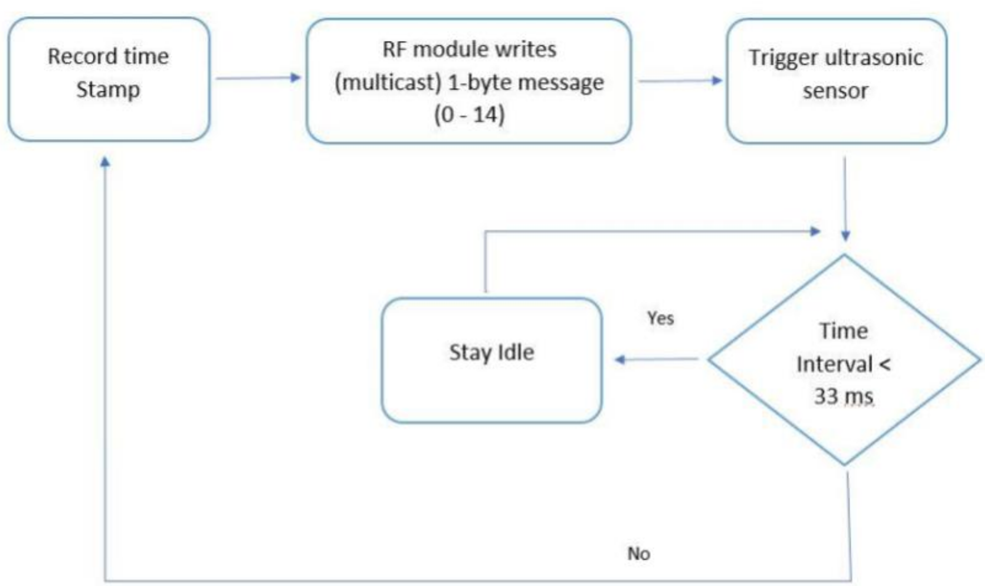

Fig 14: Flow chart of beacon component

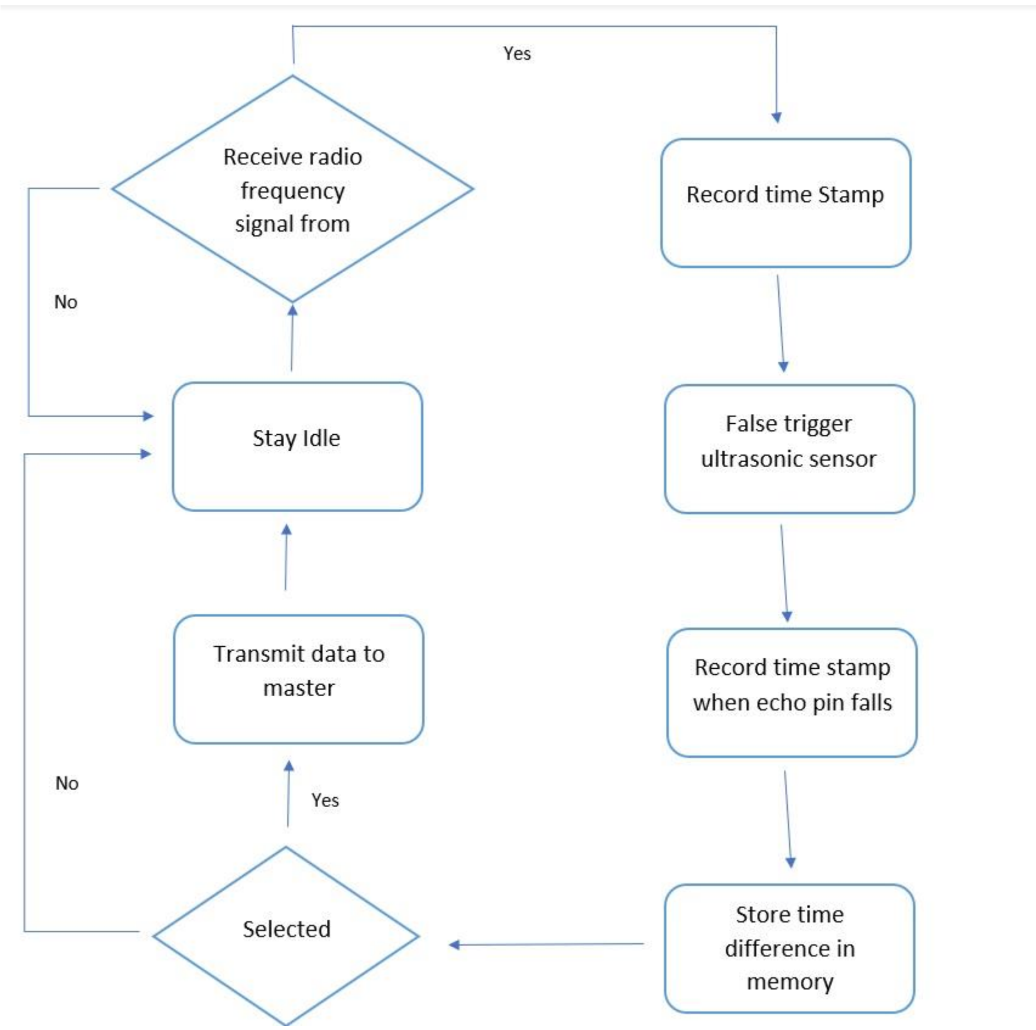

Fig 15: Flow chart of listener component

Appendix C - RV table

Power System

Requirement	Verification
DC power supply at 3.3 ± 0.1 V voltage and max current > 200mA	Connect 3.3V output from power subsystem to an oscilloscope, and measure the output Vcc and I for RF module
DC power supply at 5.0 ± 0.15 V voltage and max current > 200 mA	Connect 5.0V output from the power subsystem to an oscilloscope, and measure the output. Vcc for ATMega328, ultrasonic module, and Bluetooth module

Beacon System

Requirement	Verification
Transmit the radio frequency signal at 30 repetition rate	Increment counter variable when each pulse is sent, print the number of repetitions in 1000 milliseconds interval
Transmit the ultrasonic signal at 30 repetition rate	Increment counter variable when each pulse is sent, print the number of repetitions in 1000 milliseconds interval
Multicast radio frequency signal and ultrasonic signal to all listener components	Read RF signal and ultrasonic signal on each listener component, timeout if listener component cannot receive the ultrasonic signal

Listener System

Requirement	Verification
Receive each repetition of the ultrasonic signal	Increment counter variable when each pulse is sent, print the number of repetitions in 1000 millisecond interval, the counter value should be identical to beacon component
Receive each repetition of the radio frequency signal	Increment counter variable when each pulse is sent, print the number of repetitions in 1000 millisecond interval, the counter value should be identical to beacon component
Adjustment for the time delay between radio frequency signal and ultrasonic signal	Calculated distance should be within ±0.5 cm of displacement from the ultrasonic module without radio frequency
Master listener component should receive data from other listener components through radio frequency signal	Master listener component reads slave data on different pipes, check pipe number and print received data
Master listener component should communicate with host PC through Bluetooth	Connect Bluetooth device to PC, and read Bluetooth data in Matlab

Computation Subsystem

Requirement	Verification
Real-time computation of 3D coordinates	Display real-time beacon coordinates result in the Matlab graphical user interface

The accuracy of the beacon coordinate is within 5 cm in each axis and the Host PC should display the 3D coordinate point in real time	Use Programmable robot arm or motion capture camera to measure the location of the beacon, and compare it to our beacon coordinates result

Other

Requirement	Verification
Accurate placement of listener components with 0.1 ft regulation in 10x10x10 ft 3D space, and measure their coordinates accurately	Use a ruler to measure relative distances between each listener component, and measure their heights

Table 6: RV table