Ricochet

Systems Ltd.

April 23, 2007

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Re: ENSC 440/305 Post Mortem for the Ricochet Tracking System.

The attached document, *Postmortem for the Ricochet Tracking System*, outlines results of our project for ENSC 440 (Capstone Project). Our goal is to design and implement a tracking system for the ice hockey puck. The purpose of this postmortem document is to provide a summary of our project results and sets the direction for future development.

Ricochet Systems Ltd. consists of three innovative senior Engineering Science students: Ashkan Tehrani-Nejad, Kelsey James Regan and Imran Dewji. If you have any questions please contact me at (778) 288-4274 or via e-mail at ensc440-group5@sfu.ca

Sincerely,

Ashkan Tehrani-Nejad

CEO
Ricochet Systems Ltd.

Enclosure: Post Mortem for the Ricochet Tracking System

Post Mortem for the Ricochet Tracking System

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Version: 1.0

Abstract

The following postmortem outlines the current state of the Ricochet Tracking System project and explains any deviation from the original specifications. Some of the major differences include the number of transmitters in the puck, the software algorithms for receiving data and calculating position, and the number of receivers applied.

A number of changes are outlined for the second prototype of the RTS to overcome some complications we encountered with the first prototype. These changes will improve the overall system operation. With these improvements, we reflect on each of our personal experiences with the development of the Ricochet Tracking System.

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Glossary

A/D	*Analog to Digital*.
ATX	*Advanced Technology Extended.* A physical specification for computer hardware including the motherboard, case, and power supply.
EEPROM	*Electrically Erasable Programmable Read Only Memory.*
IC	*Integrated Circuit.*
NHL	*National Hockey League*. A North American league of professional hockey teams.
MCU	*Micro Controller Unit.*
PWM	*Pulse Width Modulator.*
RTS	*Ricochet Tracking System*.
Ultrasound	Sound that has a frequency above the threshold of human hearing of 22 kHz.

1 Introduction

Over the past four months, we have worked towards designing and developing a tracking system for a hockey puck. In the following sections we discuss the current state of Ricochet Tracking System and outline any modifications to the design specifications. In addition we discuss any future consideration for the next phase of Ricochet Tracking System. Finally, we consider an up-to-date project schedule, outline the project expenses and provide a comparison with the proposed budget.

2 Details of the First Prototype

2.1 System Hardware

2.1.1 Puck & Transmitter Circuit

We used CAD software and Denford milling machine to create a cavity within a hockey puck to house the battery, transmitters, and the transmitter circuit. The housing was designed in SolidWorks and TekSoft's CAMWorks was employed to generate NC machine code. The transmitter circuit and the puck are pictured in Figure 2-1 separately.

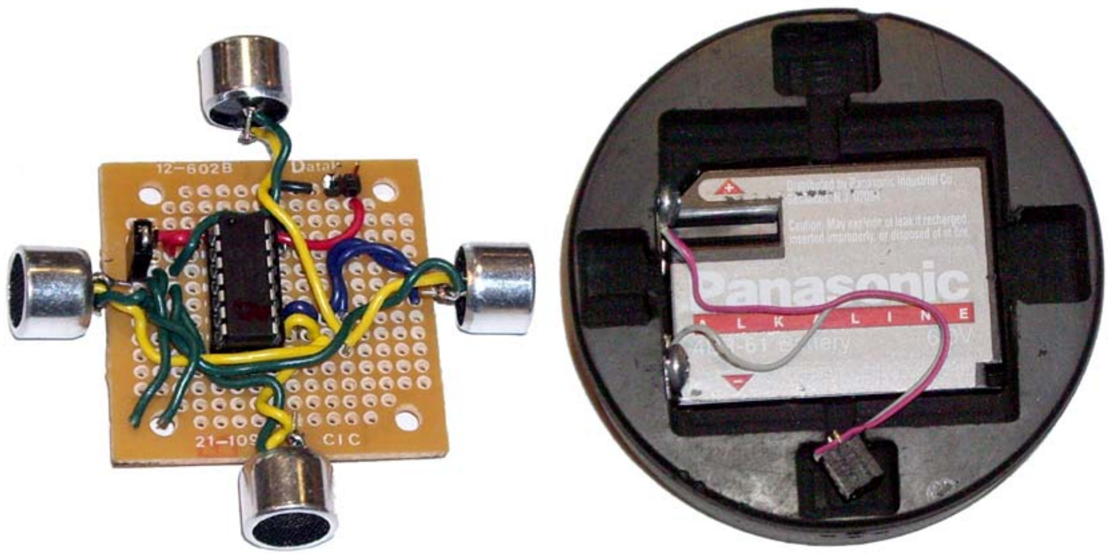

Figure 2-1: Transmitter Circuit and Puck with Battery

The battery sits in the bottom of the cavity, and the circuit is mounted on top of it. There are four channels around the battery to house the ultrasound transmitters. We were only able to include four of the six transmitters we intended to use because of space limitations. Figure 2-2 shows the assembled puck.

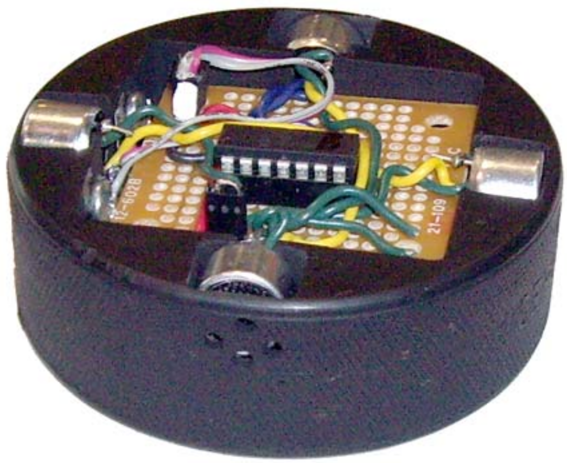

Figure 2-2: Assembled Puck

The heart of the circuit is a PIC 16F684 microcontroller which generates the pulses that drive the ultrasound transmitters. The PIC is programmed with both of the output pulses we specified in the design, though only one pulse type is used as there are only four transmitters.

2.1.2 Amplifier Circuit

The eight amplifiers are assembled compactly on 26mm by 38mm circuit boards according to the schematic in our design specification. The amplifier is built using an LM386 audio amplifier IC. Four of the eight amplifiers are shown in Figure 2-3.

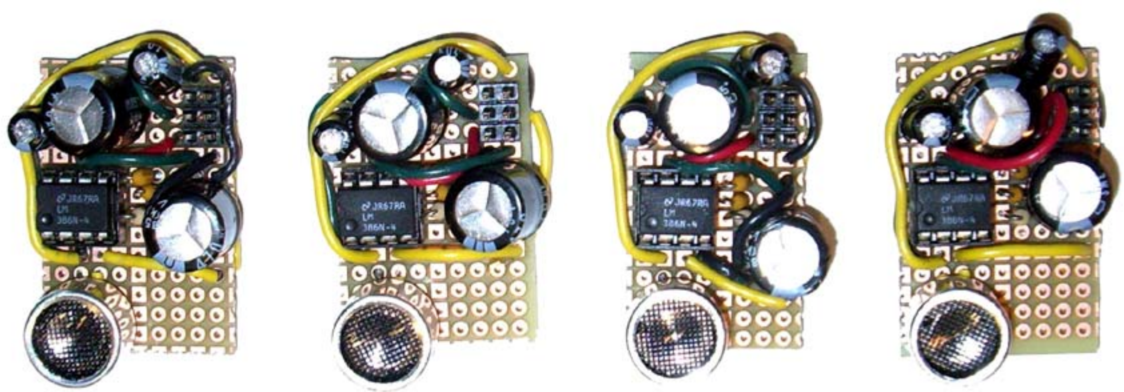

Figure 2-3: Four Amplifier Circuits

Each amplifier provides a gain of 150 to the signal picked up by the onboard ultrasound microphone, and is connected to the receiver circuit with a length of telephone cabling which also provides power to the circuit.

2.1.3 Receiver Circuit

Like the amplifiers, the receiver circuit is tightly packed onto its circuit board. The receiver circuit is composed of eight identical band-pass filters and envelope detectors, one for each amplifier. In the picture shown in Figure 2-4, four LF347 quad op-amp ICs are visible, along with two 74F14 inverter ICs at the bottom of the board.

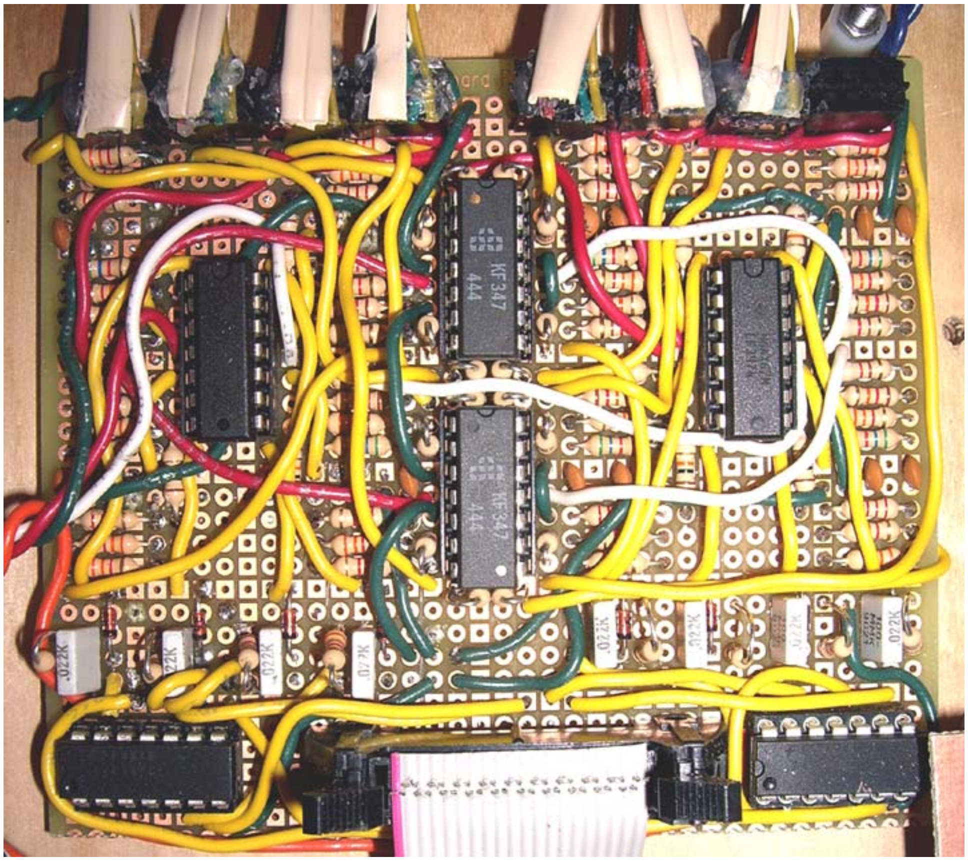

Figure 2-4: Receiver Circuit

The original specification only called for two LF347 ICs, we had to add two more to further amplify the signal to compensate for the weak signal from the transmitter circuit. In total, there are 88 resistors, 24 capacitors, 16 op-amps, 12 inverters, and 8 diodes packed onto the 9cm by 10 cm board.

2.1.4 Interface Board

We used a Motorola M68EVB912B32 evaluation board to act as the interface between the receiver circuit and the Windows PC. No modifications were required, we simply connected the receiver circuit to the evaluation board with a length of ribbon cable as shown in Figure 2-5. The evaluation board connects to the PC via its serial port.

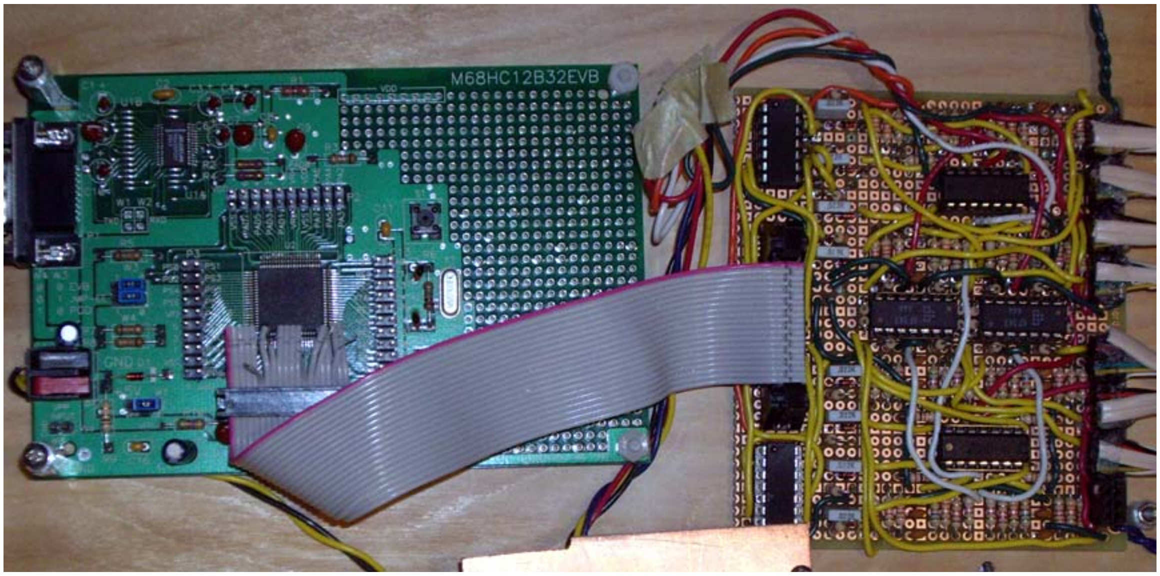

Figure 2-5: Receiver Circuit with Interface Board

2.2 System Software

The Windows PC software side of the RTS receives the data through an RS232 port, decodes it, calculates the position and finally displays various characteristics and the motion of the puck are displayed on the GUI. The program is written in C++ with the application of OpenGL libraries.

2.2.1 Serial Communication

The Motorola board communicates each sensor's received time of arrival data to the PC via RS232. A typical message sent through the serial port consists of

$,<data1>,<data2>,<data3>,<data4>,<data5>,<data6>,<data7>,

The beginning of the message is denoted with a '$' character and each segment of data is surrounded with commas. Each data segment is sent as a binary number, which needs to be decoded in the software. All data is relative to the closest sensor; therefore, there will always be a data segment set to zero, and the other sensors' data are given relative to that sensor's data.

2.2.2 Position Calculation

The Ricochet Tracking System implements a robust TDOA multilateration method in determining the position of the hockey puck from the set of data.

2.2.2.1 One Measurement

For one measurement, the Ricochet Tracking System (RTS) needs three sensors with accurate radial data corresponding to the location of the object. The coordinates of each of these sensors, or receivers, are arbitrary and known as the three vectors R_1, R_2 and R_3 with the location object, or transmitter, denoted as T. In Figure 2-6 the tracking problem is depicted.

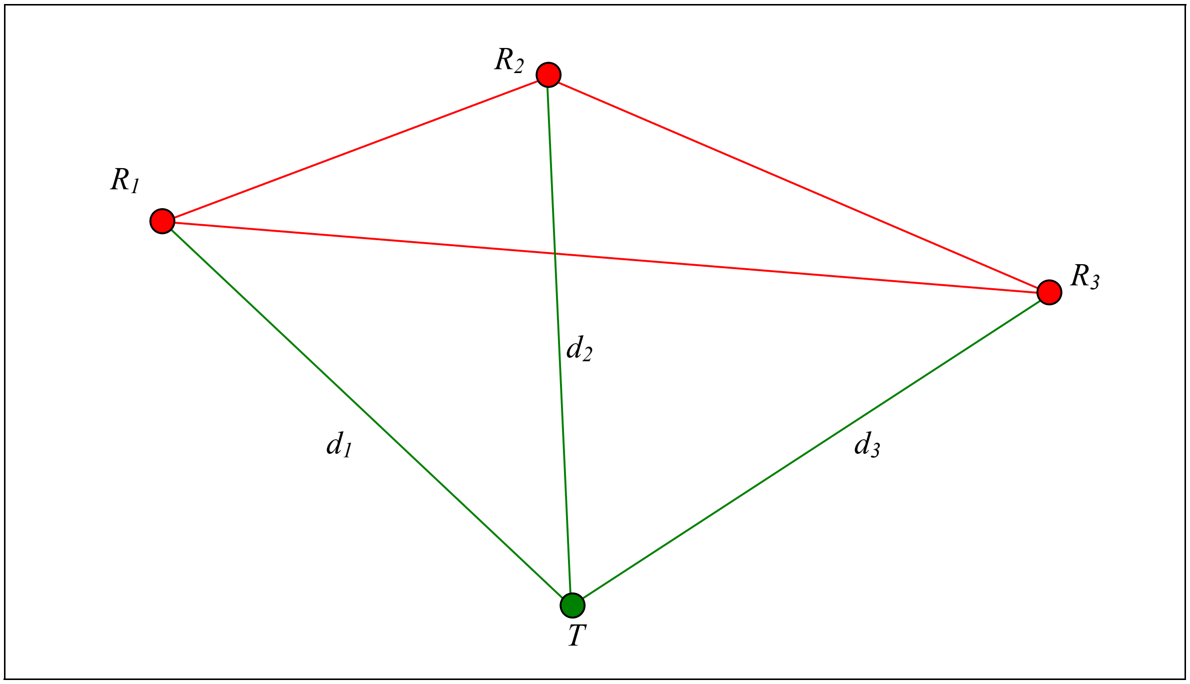

Figure 2-6: The tracking scenario with only three receivers.

The distances from any of the receivers R_1, R_2 and R_3 are known as d_1, d_2 and d_3, respectively.

To begin the investigation of the position of T, more information of this very random pyramid needs to be established. First a line is drawn from T orthogonal to the line R_1R_2 and the point of intersection will be P. Another line from P is drawn to R_3 along with a line from T to and orthogonal to PR_3. Two angles are also noted, one being subtended between R_1T and R_1R_2 named θ, and another between R_3P and R_3T named β. These variables are shown in Figure 2-9.

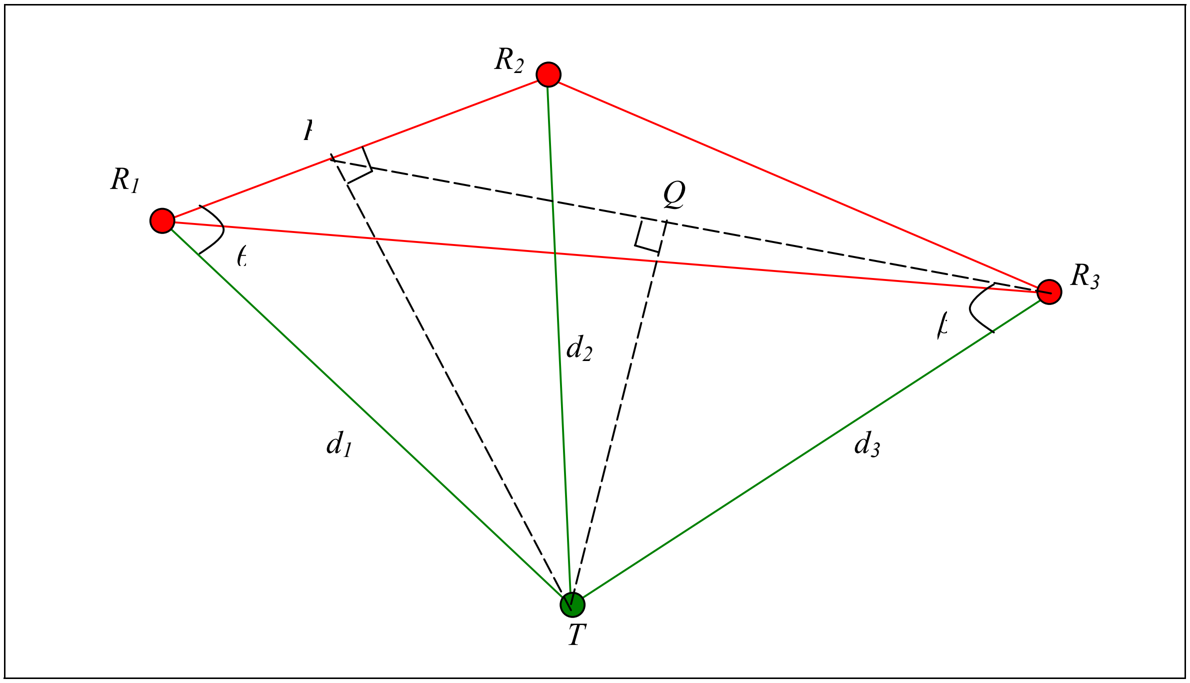

Figure 2-7: More variables added to the tracking scenario with only three receivers.

To find θ, the cosine law is applied to the triangle R_1R_2T

$$d_2^2 = d_1^2 + |R_1R_2|^2 - 2d_1|R_1R_2|\cos\theta$$

and solving for θ,

$$\theta = \cos^{-1}\left(\frac{d_1^2 + |R_1R_2|^2 - d_2^2}{2d_1|R_1R_2|}\right). \qquad (1)$$

Using equation (1) we can solve for the lengths of TP and R_1P as

$$|TP| = d_1 \sin\theta \text{, and} \qquad (2)$$

$$|R_1P| = d_1 \cos\theta, \qquad (3)$$

respectively. Using the latter length, the vector R_1P is determined as

$$R_1P = \frac{R_1R_2}{|R_1R_2|}|R_1P|. \qquad (4)$$

The middle line is then determined through the summation of vectors in a triangle

$$TR_3 = R_1R_3 - R_1P\,. \qquad (5)$$

Applying the cosine law again, we can now find the angle β by

$$|TP|^2 = d_3^2 + |PR_3|^2 - 2d_3|PR_3|\cos\beta\,,$$

and solving for β,

$$\beta = \cos^{-1}\left(\frac{d_3^2 + |PR_3|^2 - |TP|^2}{2d_3|PR_3|}\right). \qquad (6)$$

In the same manner, the lengths of QT and PQ are found as

$$|QT| = d_3 \sin\beta\,, \text{ and} \qquad (7)$$

$$|PQ| = |PR_3|\cos\beta\,, \qquad (8)$$

respectively. The vector PQ is now found as

$$PQ = \frac{PR_3}{|PR_3|}|PQ|\,. \qquad (9)$$

Now the triangle PQT is projected onto the surface defined by R_1, R_2 and R_3 to form the triangle PQT'. This triangle is shown in Figure 2-8.

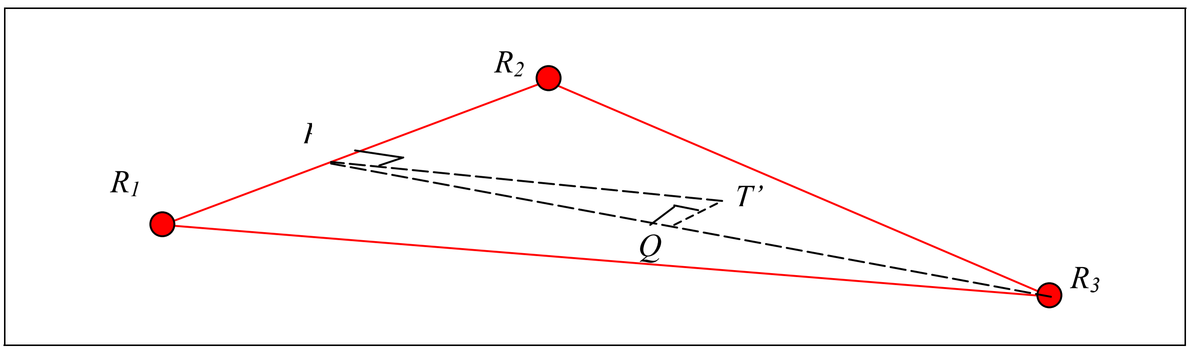

Figure 2-8: The triangle of *PQT'* in the tracking scenario with only three receivers.

The vector normal to the surface defined by R_1, R_2 and R_3 is given by the normal vector, n,

$$n = \frac{R_1R_2 x R_1R_3}{|R_1R_2 x R_1R_3|}\,. \qquad (10)$$

Using the angle subtended by the projection of *PT* to *PT'* as σ, through the equation of a projection of a line onto a surface

$$\cos\sigma = \frac{PQ \cdot PT'}{|PQ||PT'|}. \quad (11)$$

The length of PT' is not known as of yet. However, since *PT'* is perpendicular to R_1R_2 and n, a unit vector in the direction of *PT'* is known as

$$\frac{PT'}{|PT'|} = \frac{R_1R_2xn}{|R_1R_2xn|}. \quad (12)$$

Applying this, we can solve for *PT'* to be

$$PT' = \frac{PT'}{|PT'|}\left(\frac{|PQ||PQ|}{PQ \cdot \frac{PT'}{|PT'|}}\right). \quad (13)$$

Now the length of *T'T* is known through the geometry of a right angle triangle

$$|T'T| = \sqrt{|TP|^2 - |PT'|^2}. \quad (14)$$

And, since the vector *T'T* is normal to the surface defined by the receiver triangle, its direction is parallel to n

$$T'T = n|T'T|. \quad (15)$$

Finally, the vector from the origin to *T*, which would be the location of the object, is given by

$$T = R_1 + R_1P + PT' + T'T. \quad (16)$$

A final figure showing all variables is shown below.

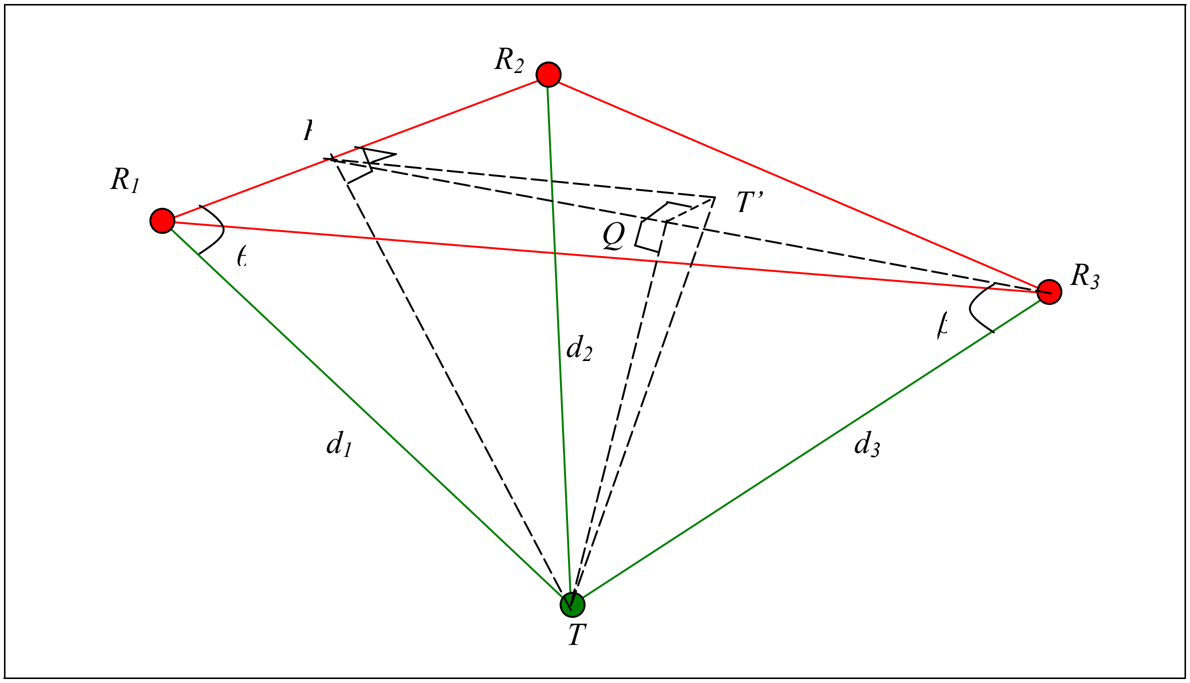

Figure 2-9: More variables added to the tracking scenario with only three receivers.

2.2.2.2 Two solutions

There are actually two solutions to Figure 2-9. One solution is found by applying a positive *n* from equation (10) to find *T'T* in equation (15) and another is found by using a negative *n*. The decision between the two solutions becomes trivial when you solve with another set of sensors explored in section 2.2.2.3.

2.2.2.3 Improving Accuracy

In theory, the above vector solution is exact. However, in the real scenario of ultrasound, there will be objects in the way, which alter the signal's velocity. To resolve this, if we assume that the error is constant to each sensor, an error term, ε, is introduced to each of the distance measurements. A second set of three receivers is then solved for to find a second *T*. The *T* from the first set will be referred to as T_1 and T_2 a solution from the second.

If the distance between these two measurements is larger than a previously defined threshold, ζ, then ε needs to be increased or decreased, depending on which brings the two *T*s closer. The amount it is altered by is half the distance from T_1 to T_2, because this will avoid overshooting in the worst case scenario of when *T* is in the plane of the receivers.

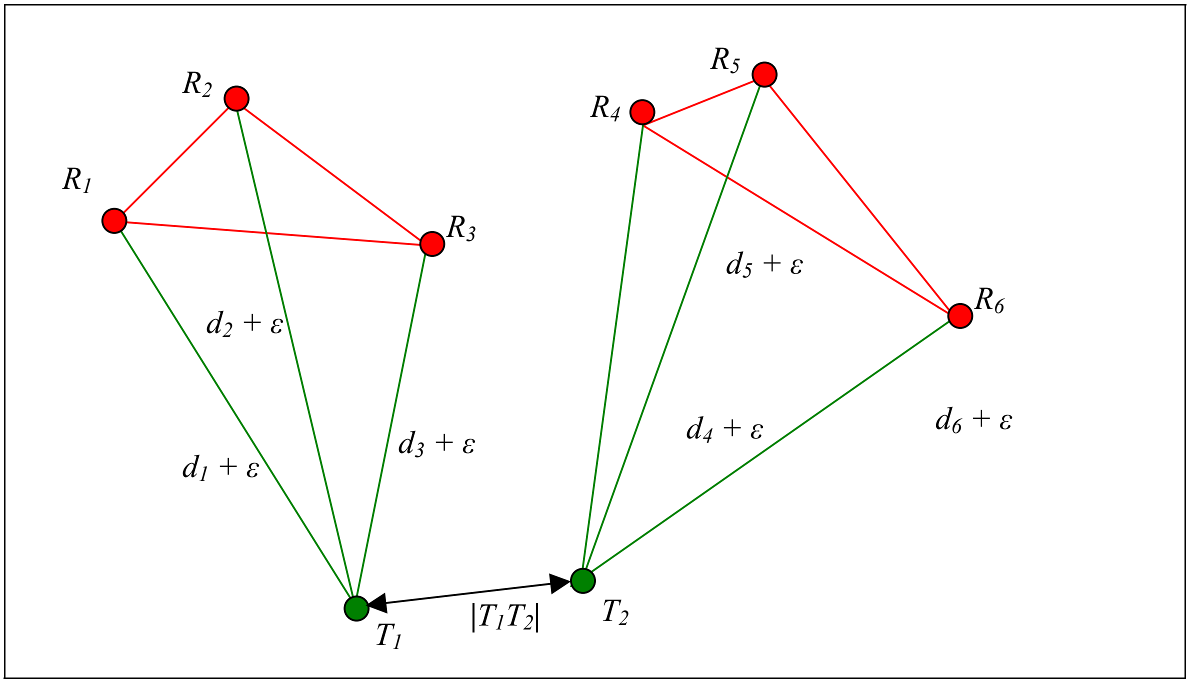

Figure 2-10: The tracking scenario with only two sets of three receivers.

Below is a flowchart describing the means of finding the error term. Trivial components of the algorithm are not included for clarity. For instance, finding the sign of the error term or if T_1 and T_2 are not getting closer, then end the algorithm.

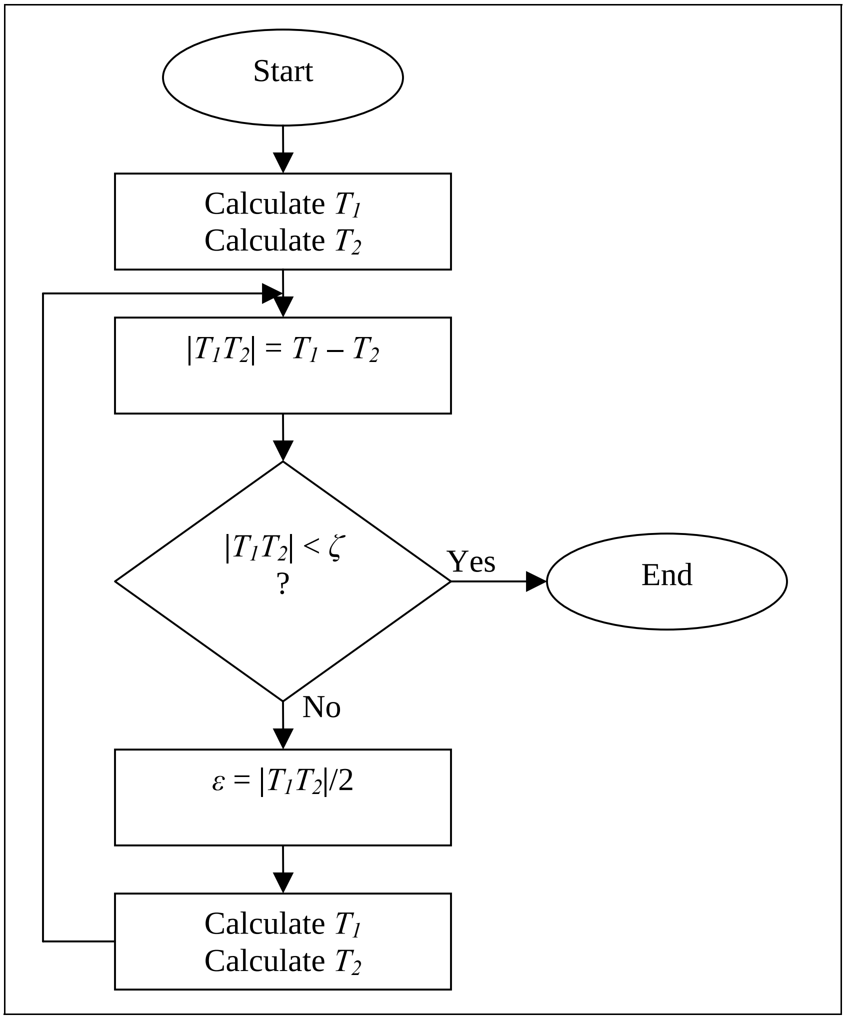

Figure 2-11: A flowchart showing the algorithm of finding the error term.

Each time new data is received and the algorithm in Figure 2-11 is repeated, the ε from the last repetition is applied as a starting point. This is done to decrease the time needed to find a successful ε and is a viable method since the Δt between successive data messages is very small.

2.2.2.4 Individual Receiver Error

Aside from the constant error term ε, there is likely to be error, ς_n, characteristic to each individual receiver, R_n. This term will be defined during the calibration sequence, when the object is placed in a central position of the environment where it is being tracked and all sensors are to take sample readings. Since the true coordinates of the central position are known, the true d_n, which will be referred to as D_n, for each R_n is known; therefore, each ς_n is calculated as

$$\varsigma_n = D_n - d_n . \qquad (17)$$

2.2.2.5 No Solution

There is no solution to the tracking method when the three spheres with centers defined at R_1, R_2 and R_3 and radii by d_1, d_2 and d_3 do not intersect. To allow for a solution, the assumption is made that the object at T is on the plane defined by R_1, R_2 and R_3, which would be the worst case scenario. Then, to force a solution, ε is fixed so T is on the plane or as close as possible. This is depicted in Figure 2-12.

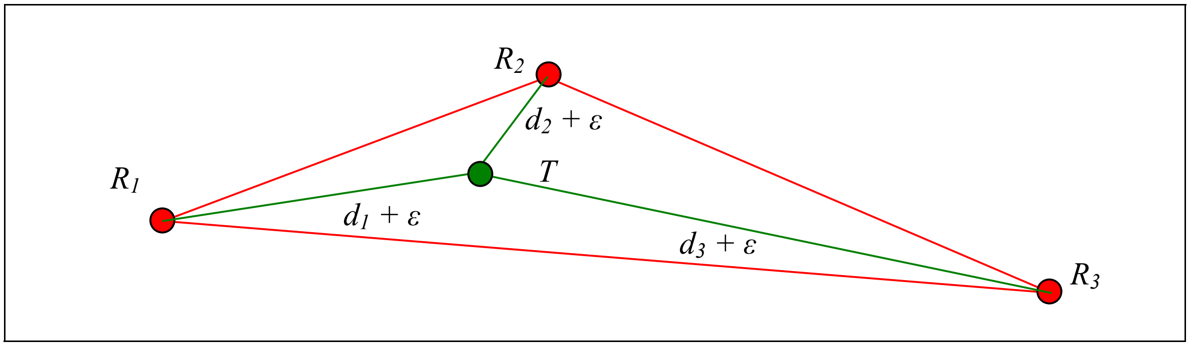

Figure 2-12: Forcing a solution to the problem when there is no solution.

2.2.3 Graphical User Interface

The GUI is implemented through OpenGL libraries and is shown below. Information regarding the sensors, serial communication and the puck is available on the right. Some options to hide the puck, walls, objects, etc is also found on the right. Display modification, including rotate, pan and zoom are shown on the bottom.

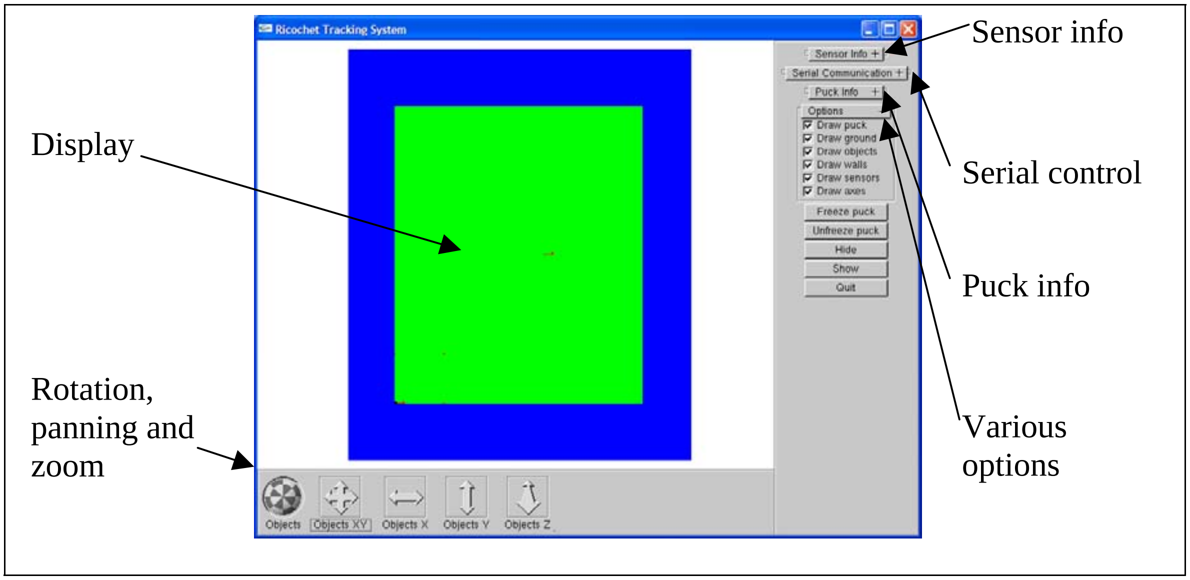

Figure 2-13: OpenGL application for the Ricochet Tracking System.

3 Deviation from the Original Design

3.1 System Hardware

3.1.1 Puck/Transmitter Circuit

Our design for the transmitter circuit called for there to be six transmitters: four mounted in a plane around the puck, and two mounted above and below the circuit pointed perpendicular to the planar transmitters. The transmitters we purchased are larger than we would like, so we were not able to fit the vertical transmitters within the volume of the puck. However the circuit does have the necessary outputs to drive the additional transmitters.

3.1.2 Amplifier Circuit

The simple LM386 amplifier circuit worked as we expected, so we did not have to make any modifications to this part of the system.

3.1.3 Receiver Circuit

The receiver circuit required a few modifications to operate as we expected. The first change we made was to substitute LF347 op-amp ICs for the LM327 ICs specified for the band-pass filters in the design. The LM327 caused the output of the filter to be heavily distorted. Fortunately, the LF347 is pin-compatible with the LM327, so no changes to the circuit board were required.

The second modification we made was to add an additional amplifier stage to each input channel with a gain of 8. The signal transmitted by the puck was much weaker than we expected, so adding this stage compensated for the weak signal. Each amplifier stage is built around an op-amp in the familiar inverting configuration. Again LF347 ICs were used.

3.1.4 Interface Board

Because of the unusual implementation of the timer component in the HC12 microcontroller, we were only able to use seven of the eight input channels. The eighth channel is used to control the timer period, so it cannot be used as in input. The software we wrote for the interface board is capable of capturing data on eight channels, but was limited to seven because of this hardware limitation.

3.2 System Software

Originally, the train of thought was that the crystals on the puck and the Motorola board would be synchronized with low enough error so that triangulation would be able to be applied. Soon we found that this was in fact very not true. So instead of applying the time of arrival scheme in triangulation, a time difference of arrival method through multilateration is applied instead. This makes way for a more robust accurate system, due to the fact that any error term consistent with each sensor is removed and the drift between crystals is acceptable.

4 Goals for the Second Prototype

The initial design of the Ricochet Tracking System allowed us to make a working first prototype, but there are several changes we would like to make for the second prototype. Instead of trying to modify the first prototype, using the lessons we have learned to build a second prototype will result in a much better system. There are four key issues that need to be addressed: the transmitter power, clock synchronization, microcontroller selection and the interface board.

4.1 Transmitter Power

As constructed, the transmitter draws less than 3mA from its 6V battery. In our design we expected the circuit to draw closer to 20mA, and we expected the signal from the transmitters to be much stronger. This circuit can be redesigned with stronger drivers, without a huge impact on battery life. The battery we have used will last 200 hours with a 3mA current draw. We can safely increase the current draw by ten times without reducing the battery life too much.

4.2 Clock Synchronization

A simple way to synchronize the clocks of the transmitter and receiver circuits is to transmit a pilot signal at a radio frequency from the transmitter to the receiver. The pilot signal will travel at the speed of light, which is roughly one million times faster than the speed of sound. The time of flight of the pilot signal will be so small it can be neglected, allowing us to measure the time of flight of the ultrasound signal relative to the pilot signal.

4.3 Microcontroller Selection

The PIC and Motorola microcontrollers we selected lack the features we require to scale-up the size of the RTS. The PIC's instruction set is very limited and it's feature set is rather primitive. Similarly, the Motorola HC12 contains only one timer, and only has seven usable inputs. Our second prototype should be built with a more modern microcontroller in the transmitter circuit, and a more feature-rich microcontroller on the interface board.

4.4 Interface Board

To save time and money we used the same Motorola HC12 evaluation board used to teach ENSC 151. Though it has most of the features we need, its inputs are limited, and the board has several features which we do not need. For a second prototype, we would like to build a custom interface board with a different microcontroller, integrated with the receiver circuit to make the system more compact.

5 Budget and Scheduling

5.1 Budget

We were able to complete the Ricochet Tracking System significantly under budget by making use of free electronic component samples offered by manufacturers, and recovering parts from discarded electronics. Table 5-1 lists our budgeted and actual expenditures.

Item	Budget	Actual
Accelerometer	$60	-
Ultrasonic Transmitter & Receiver	$150	$84.30
Circuit components	$50	$33.90
Miscellaneous	$30	$15.25
Total	$290	$133.45

Table 5-1: Budgeted and Actual Expenses

Early in our design we removed the accelerometer from the transmitter to simplify the design, so that allowed us to reduce our costs. The cost of the ultrasonic transmitters and receivers was also less than expected. Most of the circuit components were either recovered or sourced from the lab stores for free, and were able to borrow a HC12 evaluation board from Lucky, keeping our total costs down.

5.2 Scheduling

Nearly all of our tasks were completed on schedule, save for our integration testing. We had problems with the method we were using to calculate the position of the puck, which delayed the finish of our project by ten days. Our final schedule is shown in Figure 5-1.

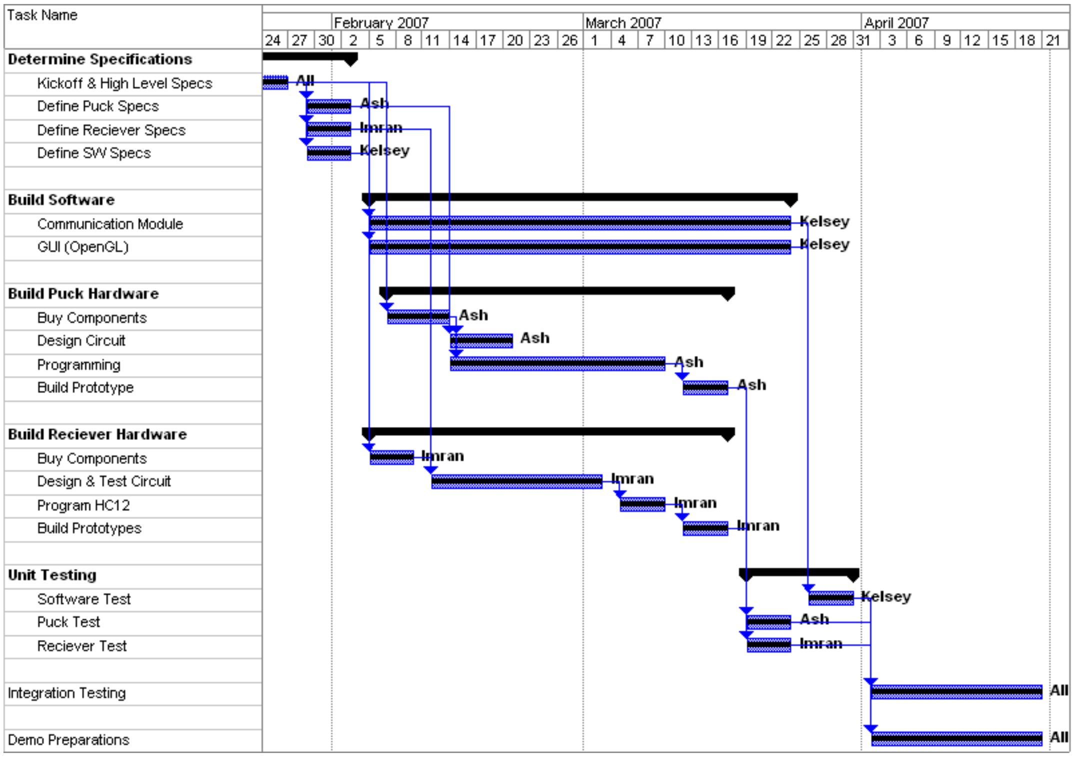

Figure 5-1: Final Project Schedule

6 Interpersonal and Technical Experiences

6.1 Ashkan Tehrani-Nejad (CEO)

I must admit that my capstone project experience is one the greatest highlights of my undergrad studies, a new experience with old friends and colleagues. Our triple dream team was formed more than year ago during our third year as an undergrad student. Prior course project team, proven to work came together once again. One of the kind team dynamics and complementing skills of team members was just meant to be able to take on any challenge. The can-do-attitude of team members toward the obstacles encountered on the way, provide and excellent project experience. With absolutely no conflicts throughout the semester and overcoming challenges one after the other it just seems too good to be true. Enthusiasm, professionalism and leadership are just few of the many attributes of our team members.

As the CEO of Ricochet Systems I had to make sure everything is going according to schedule and the overall project is rolling forward smoothly, however this task soon was proven to be much simpler than I expected with our self motivated team members. The overall project was divided into three subsystems and was assigned to the team members according to their expertise. Although each member took care of majority of his tasks independently, teamwork was the key to many of our accomplishments.

As the three subsystems overlap, great portion of our project was done involving all members. I was principally in charge of puck subsystem. Throughout the design and implementation process I was exposed to many practical design issues that I learnt a great deal from.

Although the final results are far from perfection, the project is a success in my perspective. I enjoyed the experience I had throughout this project with all team members.

6.2 Kelsey James Regan (CTO)

This project has given me a chance to work with a great team, who is eager and knowledgeable. Imran, Ashkan and I worked very well together, since even though we had well defined individual tasks, we still were able to quickly jump into another group member's area and help them where they were stuck. My knowledge regarding applicable filter and amplifier circuits, C++ and HC12 programming, and overall system design methodology has been immensely expanded. I enjoyed working with this group, and would love to work with them again.

6.3 Imran Dewji (COO)

The most valuable lesson I learned in building the Ricochet Tracking system is that I, along with my team members Ashkan and Kelsey are capable of successfully completing such a project. At the beginning of the semester I had only bits and pieces of knowledge collected in each course I have taken, this capstone project has allowed me to put everything together in a real engineering project.

Working in a team requires a great deal of trust among the team members. Though each of us has a title, and Askhan is the CEO, we worked as equals throughout the project. I knew that Kelsey and Ashkan were well motivated and would complete their share of the work which allowed me to do my own tasks well.

This project allowed me to expand my knowledge of circuit design, microcontroller programming, and signal processing. I also had the opportunity to research and evaluate different positioning techniques and technologies in designing the RTS. If I had the opportunity to do this project again, I would do it with the same people, and we would build a far superior tracking system because of the experience we have gained.

7 Conclusion

In conclusion, we have designed and developed a working prototype, which proves the concepts and technologies that we set out. The first prototype provides us with a solid base, which we can improve and expand upon with the modifications outlined in this document.

As a team, Ricochet members have worked well together and enjoyed this project experience. We started as friends and colleagues and are looking forward to working together in the future.