# Mechatronic Football Ultrasonic Positioning System

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May 10, 2012

### Abstract

The purpose of this project was to create a team of mechatronic football players to compete in the first intercollegiate mechatronic football game. This was the first year that two teams from different universities, namely the University of Notre Dame and Ohio Northern University, to play against each other in Stepan Center on April 20th, 2012. A team of 12 senior Mechanical Engineering students from Notre Dame designed and constructed a mechatronic football team based on the designs from previous years within 14 weeks and under a budget of $ 4,000. This year a brand new positioning system was implemented on the robots in order for them to determine their positions on the playing field and execute plays autonomously. The primary components of the positioning system are ultrasonic beacons on the playing field and ultrasonic receivers on the robots. The major advantage of this system is that it is much faster to start an offensive play before the defensive players can respond promptly. The purpose of this report is to present a detailed description of the hardware of the existing system, point out its limitations and problems, and provide potential solutions and recommendations to modify and improve the system next year. The trilateration algorithm and software implemented on the system is introduced in a separate report.

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# Acknowledgments

The primary contributers to the work presented in this report were the members of the Electronics Design Team: Waylon Chen and Yichao Pan. The Programming Team contributed to the trilateration algorithm and software implemented on the system. Technical assistance in electronics was provided by Mr. Gregory Brownell. Additional feedback was provided by course instructor Prof. Michael Stanisic, as well as Intercollegiate Mechatronic Football League Commissioners: Skip Horvath, Bill Hederman and Vince Cushing. Collaboration with the other Senior Design project team members contributed to the successes achieved on the game day.

# Contents

# 1 Introduction

This ultrasonic positioning system was inspired by the infrared and ultrasonic detection system used on the Quarterback and Wide Receiver in the previous year. The previous system had trouble locating the robots quickly. By the time that the Quarterback detected the Wide Receiver, it might be sacked by a defensive player already. The ultimate purpose of developing a brand new positioning this year was to speed up the process so that the Quarterback could quickly deliver the ball to the Wide Receiver. Also, the system has the potential for future development to realize autonomous line-up of the entire team and even actual plays. The final version of the system achieved part of this purpose due to the time and budget constraints. This section provides a general overview of the system and the primary challenges encountered in the development process. More detailed explanations for the major hardware components of the system can be found in the following sections.

## 1.1 Original Idea

The original idea of this positioning system was to measure the distances between each robot and multiple known locations outside the playing field, and use the trilateration method to determine the location of the robot relative to a reference point on the field. Theoretically, three locations outside the playing field should be sufficient to determine a robot's absolute position relative to the three locations, but more than three locations might be used to introduce redundancy in order to increase the accuracy and the reliability of the system. The ideal situation would be that a central remote control initiated a starting signal, and all the offensive players could determine their positions and line up along the line of scrimmage. Another signal from the central remote control would initiate an autonomous play of the offensive players, which would execute the pre-determined routes. Human controllers would play a minimal role in the execution of the plays under full operation of this system.

## 1.2 Final Delivery

Due to the time and budget constraints and various unexpected problems throughout the development process, the final version of the system only had three beacons, one stationary and two human-mounted, as well as receivers on three robots. The receivers were implemented on three major robots, namely Quarterback Sleepy Jim, Wide Receiver Michael Droyd and Wide Receiver Megatron. Because of the limited coverage, the beacons were moved along with the line of scrimmage. The purpose of the system was to determine the relative distance and orientation between the Quarterback and the Wide Receivers, so that the Quarterback could adjust the turntable orientation and the speed of its throwing wheels on the turntable accordingly and deliver the ball accurately to a Wide Receiver. The whole process was intended to operate within two seconds after the Quarterback and Wide Receivers are in position, so it would give the offensive side a tremendous advantage over the defensive side, assuming the system was consistently reliable.

## 1.3 Logic of System

The distance between a beacon and a receiver was calculated by multiplying the speed of sound by the travel time of the ultrasonic signal. A central remote control was used to initiate an ultrasonic signal from each of the three ultrasonic beacons. The remote control communicated with both beacons and robots by Zigbee protocol. Therefore, both beacons and robots should have Zigbee antennas on board. The basic logic of the control procedure is presented below:

(1) The controller initiates an ultrasonic signal from the first beacon using the central remote control. Once the beacon receives the Zigbee signal from the remote control, it broadcasts an ultrasonic signal to the Quarterback and Wide Receivers on the field through the ultrasonic transmitters.

(2) Meanwhile, the Quarterback and Wide Receivers on the field receive the same Zigbee signal from the central remote control as well. Once the signal is received, the robots start counting the time using their timers on board.

(3) Each robot waits for the ultrasonic signal from the beacon while running the timer. Once the ultrasonic signal is received through the ultrasonic receivers on board, the robot stops the timer and computes the travel time of the ultrasonic signal based on the number of timer counts.

(4) The speed of sound is assumed to be 340 m/s (or measured on the playing field prior to the game to obtain a more accurate indoor speed of sound). The distance between the beacon and each robot is calculated by multiplying the speed of sound by the travel time corresponding to that robot.

(5) Repeat (1) through (4) using a different beacon, until all the beacons are used.

(6) With three distances corresponding to each robot, the position of each robot can be computed using the trilateration code loaded in the micro-controller on its main board.

(7) Upon knowing its position, the Wide Receiver communicates its position to the Quarterback, who then adjusts its turntable and throwing wheels to execute a pass.

This procedure was only applied to the Quarterback and Wide Receivers, but as long as there is sufficient hardware and coverage, it may be implemented on all the offensive robots on the playing field. The precision of positions was expected to be within a few inches.

## 1.4 Primary Challenges

The idea seemed to be quite simple when the project was initiated. However, the scope of the application kept changing along with the progress of the development. The major challenges involved in the development process for the hardware include:

(1) Coverage of the system: Each ultrasonic transducer has a beam pattern, which significantly limits the coverage of the ultrasonic signal. How is the signal to be broadcast on the playing field? What could the optimal coverage be? It was affected by the number of beacons used in the system, the number of ultrasonic transducers used on a beacon/receiver, the voltage applied to a beacon/receiver, and etc. The coverage directly determined whether the beacons should be stationary or mobile.

(2) Application of multiple transducers: If multiple ultrasonic transducers were implemented on each beacon or receiver, would the circuit be capable to power them simultane-

ously? What voltage should be applied to the circuit? Would the signal emission or reception be radically different than using one transducer? No examples were found in literature regarding application of multiple ultrasonic transducers.

(3) Installation of beacons and receivers: All beacons could be stationary around the playing field if the robots could receive signals from the beacons anywhere on the playing field. If the coverage were not able to be increased to cover the whole playing field, how should the beacons be positioned? A possible solution would be mounting the beacons on human operators, thus moving the three reference positions wit the robots as they progress down the playing field. How should the human-mounted beacons be set up without exposing the electric components to damages? The receivers were installed on the robots directly. How can a good signal reception be ensured as it was observed during testing that slight variations in the level and tilt of beacons significantly changed the range of the system? How should the receiver system be incorporated to the various existing designs of robots? This challenge was encountered mainly in the second half of the development process, after a prototype of the system was built.

The major components of the system shall be divided into four parts: (1) beacon circuit, (2) receiver circuit, (3) transducer arrangement and (4) installation. The following four sections will be dedicated to these four topics.

# 2 Beacon Circuit

This section presents a description of the beacon circuit and the design methodology used in the development process.

## 2.1 Overview

The function of the ultrasonic beacons is to broadcast ultrasonic signals to cover the whole playing field, ideally, so that all the robots on the team can receive the signals. Figure 1 illustrates the dimensions of the playing field. The maximum range between a beacon and a robot can be 106 ft ($\sqrt{94^2 + 50^2}$ ft), if the beacon and the robot are placed at two opposite corners along the diagonal of the playing field, excluding the end zones. Whether or not the ultrasonic signals can cover the whole field depends on the sound pressure level of the transmitters and the sensitivity of the receivers. Both transmitters and receivers are ultrasonic transducers. An ultrasonic signal with a higher amplitude can travel further than that with a lower amplitude, before the signal becomes undetectable. A transmitter with a higher sound pressure level can generate a signal with a higher amplitude, and thus the signal can reach a longer range. The amplitude of the signal decreases along with the travel distance, following the inverse-square law [1]. This basically means that each time the distance is doubled, the signal amplitude at the end of the distance will be reduced by a factor of four (-6dB). Therefore, the sensitivity of the receivers also has a huge impact on the range that can be realized. The actual range of the system was determined experimentally after a prototype was constructed. Whether the beacons should be stationary or mobile totally

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[1] http://www.primacoustic.com/cumulus-science.htm

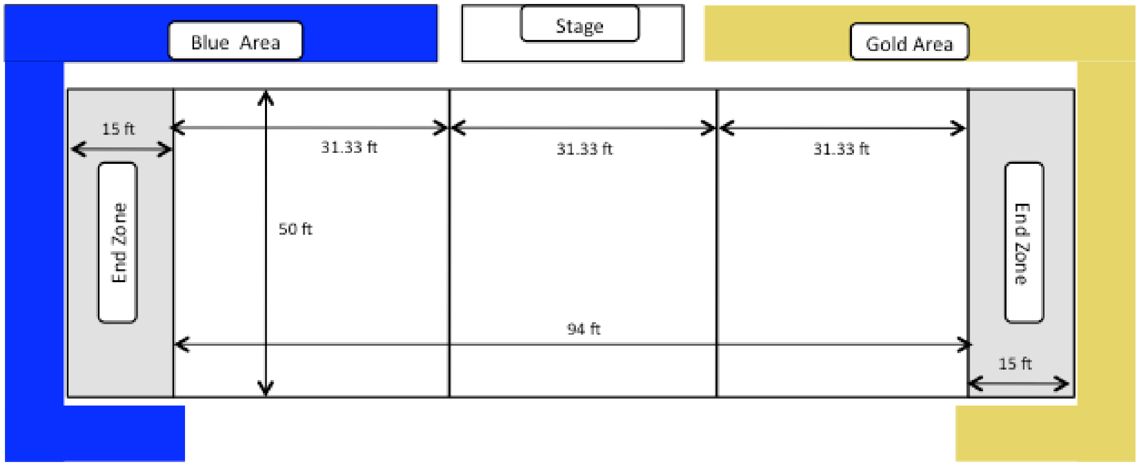

Figure 1: Mechatronic Football Game Playing Field Dimensions

depended on this range. The goal was to design a beacon with a wide coverage. The major challenges were:

(1) How should an ultrasonic signal with desired frequency be generated?

(2) How should a high voltage be applied to the transmitters to increase sound pressure level generated without damaging other electronic components?

(3) How should the signal be controlled using a remote control? How to establish a connection between the main board and the beacon circuit?

## 2.2 Circuit Design

The paramount component of the beacon is the beacon circuit, which was constructed according to Figure 2. The function of the circuit is to generate 40-kHz frequency to drive multiple transmitters simultaneously, while a relatively high supply voltage (36 V) can be applied across each transmitter. The number of transmitters used on each beacon in the final system is four, based on the beam pattern of each transmitter obtained experimentally. A detailed explanation of how this number was determined will be provided in Section 4.3 .

The heart of the beacon circuit is the PIC12F510 Microchip [2]. This microchip is programmable. A code written in Assembler (see Appendix A) [3] was loaded into the chip so that it could produce a 40 kHz signal on Pins 2, 5, 6 and 7 to drive individual transmitters. The signal can charge and discharge each transmitter at that frequency to produce a desired ultrasonic signal. The duty cycle of the signal was adjusted intentionally to reduce power consumption while the transmitters were being discharged. This was the primary reason that this design was adopted instead of the first design of the beacon circuit, which had very high power consumption that could not be adjusted. Appendix B provides a brief description of the first design of beacon circuit.

The sound pressure level of an ultrasonic transmitter depends on its driving voltage.

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[2] PIC12F510 Microchip: http://ww1.microchip.com/downloads/en/DeviceDoc/41268D.pdf

[3] This code was written by Mr. Brownell.

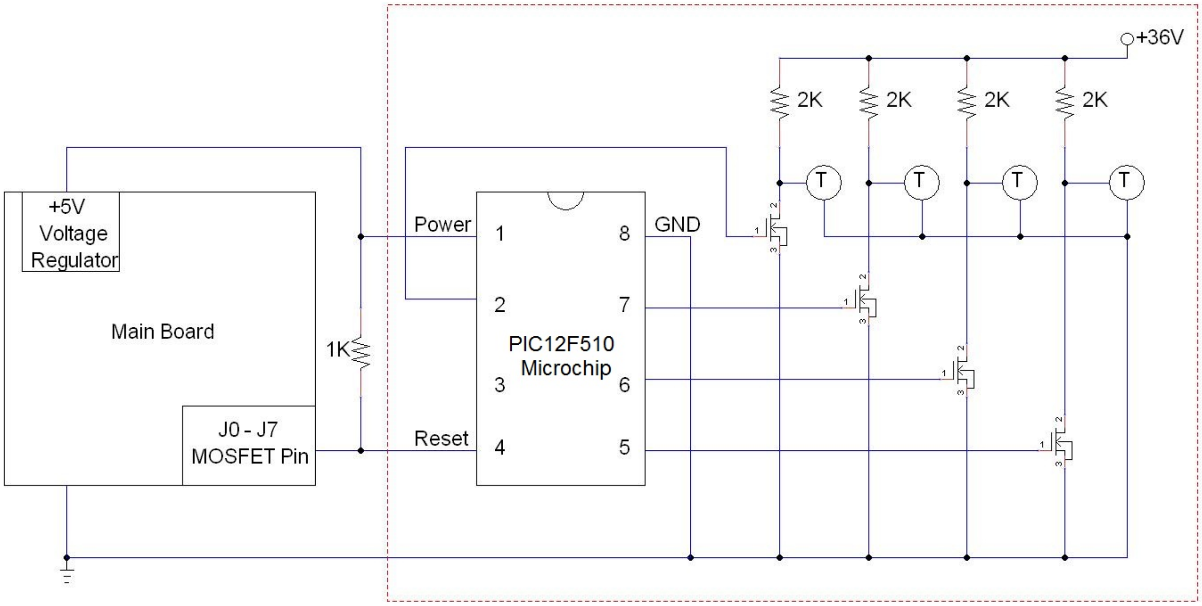

Figure 2: Circuit Diagram for the Ultrasonic Beacon Circuit

In order to apply a high voltage across each transmitter without damaging the PIC12F510 Microchip, a TN0104N3 Transistor [4] is used in series with each transmitter to act as a switch. The advantage of using a transistor is to enable a low voltage signal to control a high voltage application. TN0104N3 Transistor also has a high switching speed, which is a desired feature in this application due to the 40-kHz high frequency. The 36-V voltage is supplied by three Sealed Lead Acid (SLA) batteries. A higher voltage was not used because the TN0104N3 Transistor can only handle up to 40 V. Also, a higher voltage could impose potential hazard on human operators. Another key point is that the transistor has three leads, namely source, gate and drain. The gate is in the middle, which is connected to the output pin on the microchip. The source and drain should be connected to the ground and live, respectively. Switching the order would result in a dysfunctional circuit.

The PIC12F510 Microchip cannot handle a 36-V supply voltage, so it is powered by a 5-V voltage instead. A 5-V voltage supply can be easily obtained from a voltage regulator on the main board, which is connected to Pin 1 on the PIC12F510 Microchip on the beacon circuit to power its output signal. By using the 5-V output voltage from the main board, the total number of supply voltages was limited to two, which limited the complexity of the system.

There are eight MOSFET pins (J0 through J7) on the main board, one of which is used to control the reset pin (Pin 4) on the PIC12F510 Microchip. This reset pin is configured as a general purpose digital input, which functions as an enable input. Each MOSFET pin corresponds to a bit. When the bit is set to 0, the J pin turns off the MOSFET gate, thereby driving its open drain high. The input voltage signal is high at the reset pin, so the microchip

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[4] TN0104N3 Transistor Data Sheet: http://www.supertex.com/pdf/datasheets/TN0104.pdf

is turned off, and the transmitters do not generate ultrasonic signals. When the bit is set to 1, the J pin turns on the MOSFET gate, thereby driving its open drain low. The input voltage signal is low at the reset pin, so the microchip is turned on, and the transmitters output ultrasonic signals. Thus, the binary bit is able to control the output of the ultrasonic transmitters. It is easy to write a code for the remote control to change the value of the binary bit on the main board by a button press and control the ultrasonic signal from the beacon circuit.

Most ultrasonic transducers available on the market, including both transmitters and receivers, have an optimal frequency of 40 kHz. In order to achieve the longest possible range, it is critical to drive the transmitters at this particular frequency. Thus, the PIC12F510 Microchip is programed to generate a 40-kHz frequency. Correspondingly, the receiver board is tuned to detect an ultrasonic signal at the same frequency, which will be described in the next section.

Ultrasonic transducers basically act like capacitors, so it is critical to allow sufficient charge time for the transmitters to achieve highest voltage possible. Each line that contains an ultrasonic transmitter in Figure 2 is connected to a 36-V power supply and has a 2K-$\Omega$ resistor as well as a TN0104N3 Transistor. The transmitter could be considered as a capacitor in this case. Therefore, such a line could be considered as a simple RC circuit while the transistor was on. When the output pin (Pins 2, 5, 6 or 7) of the PIC12F510 Microchip output a high voltage, the TN0104N3 Transistor was on, and the current went from the 2K-$\Omega$ resistor through the transistor, shorting the transmitter. During this state, the transmitter was discharging. If the output pin were set to a low voltage, the transistor was off, and the circuit acted as an RC circuit. During this state, the transmitter was charging. Every RC circuit has a time constant $\tau$, which is calculated by Equation 1:

$$\tau = RC, \tag{1}$$

where $C$ is the capacitance of the 400ST160 Transmitter [5] used on the beacons, which is 2400 pF at 1 kHz. It was assumed that the capacitance value did not change when the frequency was elevated to 40 kHz. When $R$ is equal to 2K $\Omega$, the time constant for the RC circuit is 4.80 $\mu$s.

Figure 3 [6] illustrates the RC charging curve. It takes about five time constants for the voltage across a capacitor to achieve the supply voltage in an RC circuit. In this application, the charge time should be longer than 24.0 $\mu$s to charge the transmitter to 36 V. The charge time is controlled by the duty cycle of each output pin of the PIC12F510 Microchip. The duty cycle of each output pin was programed to be 6%. A 40 kHz frequency corresponds to a period of 25 $\mu$s. During one period, the output from the PIC12F510 Microchip is high for 1.5 $\mu$s and low for 23.5 $\mu$s. The transmitter is charged whenever the transistor is off, corresponding to a low voltage output from the microchip. Therefore, each transmitter has 23.5 $\mu$s charge time, which is more than 4.9 time constants. The transmitter should be charged very close to 36 V during each period.

If the resistor value were reduced, the time constant would be reduced proportionally, and the transmitter could be charged to 36 V within less than 23.5 $\mu$s. The reason that the

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[5] 400ST/R160 Transducers Data Sheet: http://www.farnell.com/datasheets/81163.pdf

[6] RC Charging Curve: http://www.electronics-tutorials.ws/rc/rc2.gif

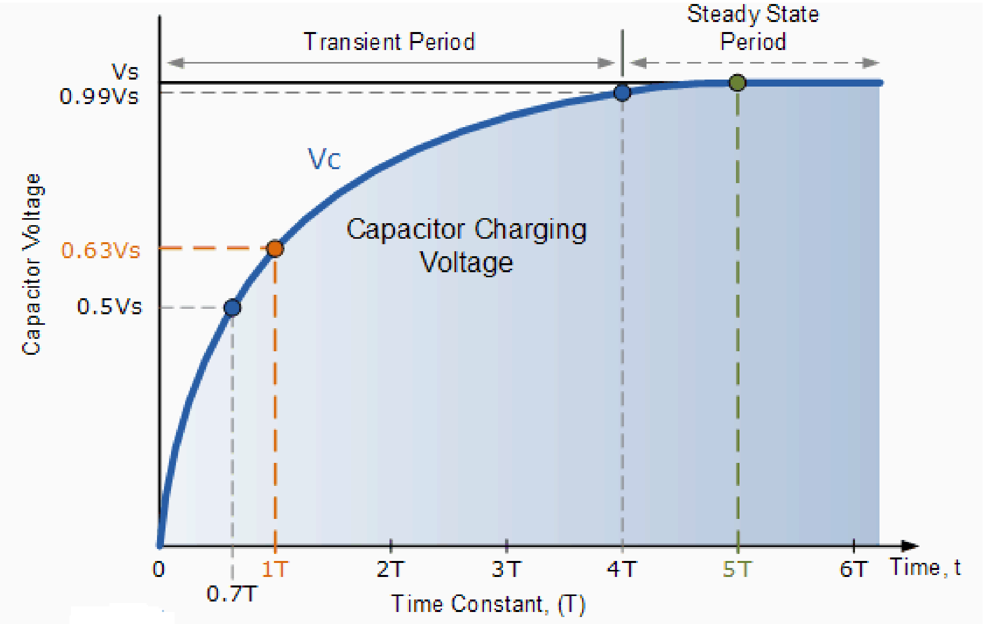

Figure 3: RC Charging Curve

2K-Ω resistors were selected was that the transmitters could be consistently charging when the transistors were turned off. If a transmitter were charged to 36 V within much less time, for example, 5 $\mu$s, then once it was fully charged, there would be no current through the circuit anymore. It might be beneficial to maintain a current throughout the entire charging phase, namely whenever the output from the microchip was low. A resistor with a different value of resistance can be used to replace the 2K-Ω resistor in order to test and see how the change influences the range of the signal.

An interesting observation was that the actual charging curve did not look as smooth as it is shown in Figure 3, when an oscilloscope was hooked up to the circuit and measured the voltage across one transmitter. The general shape of the charging curve was the same, steep at the beginning and flat at the end. However, the actual charging curve manifested by the oscilloscope demonstrated oscillation. The most probable explanation is that the ultrasonic transmitter may have some impedance in addition to capacitance, though it is not mentioned in the data sheet. The effect of this oscillation on the range of the signal was not further examined, since there was not an easy way to reduce the inherent oscillation and make the charging curve smoother.

## 2.3 Final Product

A quick recap of the logic of controlling the signal output from the beacons is presented below, assuming the MOSFET pin J1 is used on the main board to control the beacon circuit:

(1) The human operator sends out a Zigbee signal using the central remote control to initiate an ultrasonic signal.

(2) The Zigbee antenna on the main board on the beacon picks up the Zigbee signal. The micro-controller on the main board sets the MOSFET Bit J1 to high. Correspondingly, Pin J1 turns on the MOSFET gate, thereby driving its open drain low. The Zigbee antenna on the receiver also picks up the signal and starts the counter.

The input voltage signal is low at the reset pin,

(3) The voltage input at the reset pin (Pin 4) on the PIC12F510 Microchip is set to low by Pin J1. The microchip is turned on, generating a 40-kHz signal with a 6% duty cycle.

(4) The output pins (Pins 2, 5, 6 and 7) on the microchip all follow the duty cycle of this signal. The TN0103N3 Transistors are turned on and off at the same frequency.

(5) The transmitters are discharged and charged when the TN0103N3 Transistors are turned on and off, generating a 40-kHz ultrasonic signal.

A detailed view of the beacon circuit without the main board is illustrated by Figure 4. The connections to the transmitters are not present in this figure. The green wire is connected to the 5-V voltage regulator on the main board.

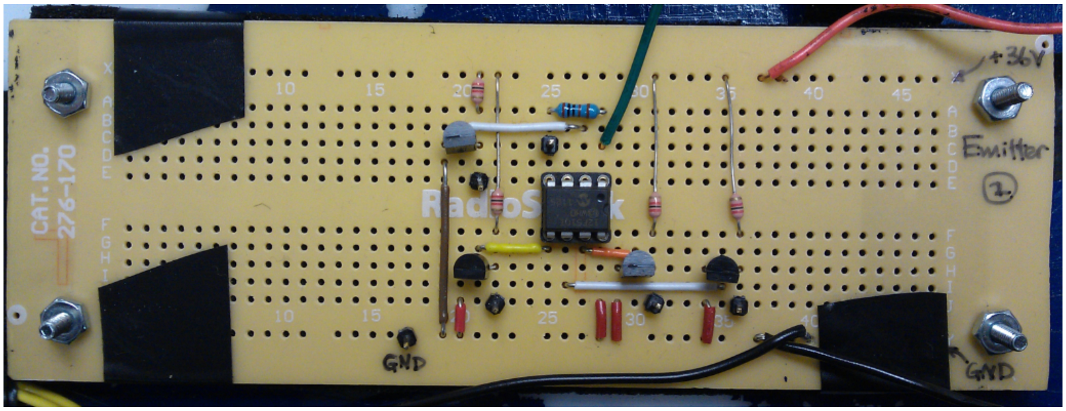

Figure 4: A Detailed View of a Beacon Circuit without Main Board

Appendix C contains a picture of the beacon circuit along with the main board.

# 3 Receiver Circuit

This section presents a description of the receiver circuit and the design methodology used in the development process.

## 3.1 Overview

Though the beacons actively control the coverage of the system, the receivers also have a huge influence on the coverage. If the beacons could generate long-range signals but the receivers were not able to detect and interpret the signals successfully, the whole system would not work well. The Quarterback and two Wide Receivers had receiver circuits on board to receive ultrasonic signals from the beacons. The major challenges involved in designing a good receiver circuit were:

(1) When the distance between a beacon and a receiver is far, the ultrasonic signal at the receiver location is supposed to very weak. How should signals detected by the receiver be amplified?

(2) The beacons emit ultrasonic signals at 40-kHz frequency. How should it be ensured that the receivers only pick up the right signals? How should influences from other sound sources be eliminated?

(3) The signal eventually would be processed in the micro-controller on the main board. What kind of signal should be sent to the main board? How should the receiver circuit be connected to the main board?

## 3.2 Circuit Design

The receiver circuit was constructed according to Figure 5 [7].

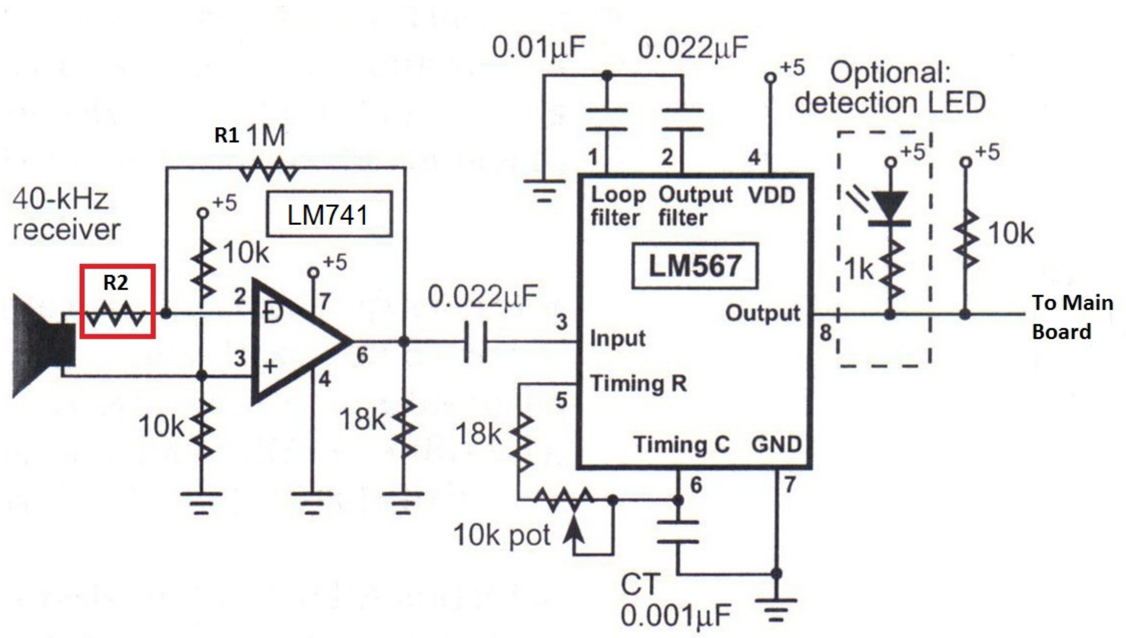

Figure 5: Circuit Diagram for an Ultrasonic Receiver Circuit

Similar to the beacon circuit, the receiver circuit also has the capability of operating multiple ultrasonic transducers simultaneously. Instead of a single receiver between Pin 2 and Pin 3 of the LM741 Op-amp, as illustrated in Figure 5, a number of receivers connected in series can be used between the two pins. Each receiver has the ability to receive an ultrasonic signal and convert that into a voltage signal. When using multiple receivers, more than one receiver may pick up the same ultrasonic signal and produce more than one voltage signal. If the signals are in phase, then they will be added together and become one stronger signal, which is a desired situation. How to ensure that the signals are in phase will be discussed in Section 4.4.

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[7] BASIC Stamp I Application Notes, Parallax, Inc.

The ultrasonic receiver - a high-frequency microphone - feeds the op-amp. The gain value of the LM741 Op-amp [8] is controlled by two resistors, $R_1$ and $R_2$. The gain value is equal to $R_1/R_2$. The original value of $R_2$ was 10K Ω, but it was completely eliminated in the final version of the receiver circuit. Theoretically, eliminating $R_2$ would result in an infinite gain value, but not in reality. The actual gain value was not quantitatively measured, but the range of the system was maximized. Though increasing the gain value might amplify the noise along with the actual signal, which was fed into the LM567 Tone Decoder [9], no significant side effect was observed in testing when $R_2$ was eliminated.

The signal from the op-amp goes to an LM567 Tone Decoder, which looks for a close match between the frequency of an incoming signal and that of its internal oscillator. When it finds one, it pulls its output pin low. The internal oscillator of the LM567 Tone Decoder is controlled by the 18K-Ω resistor and the 10K-Ω potentiometer between Pin 5 and 6. Assuming the total resistance of the resistor and potentiometer is $R$, the internal frequency $f$ is calculated by Equation 2

$$f = \frac{1}{1.1R \times CT}, \tag{2}$$

where $CT$ represents the capacitance of the capacitor connected to Pin 6 in Figure 5, which is 0.001 $\mu$F. In order to obtain an internal frequency of 40 kHz, $R$ should be equal to 22.73K Ω. This can be easily achieved by adjusting the potentiometer while measuring the internal frequency with an oscilloscope. The oscilloscope should be connected to the ground of the circuit and measure the output from Pin 6 on the LM567 Tone Decoder, while the ultrasonic receiver is not present. Basically, the left half of Figure 5 containing the op-amp is an open circuit. With AC Coupling, the oscilloscope should show a periodic triangular wave on the screen, and the frequency should be around 40 kHz. Adjusting the potentiometer until the frequency of the wave is very close to 40 kHz, which is the internal frequency of the LM567 Tone Decoder.

Figure 5 is the final circuit design. The capacitors connected to Pins 1 and 2 on the LM567 Tone Decoder were accidentally switched from the original design. The function of the two capacitors is to control the bandwidth of the tone decoder so that it is able to identify signals within a certain frequency range. The original design had a smaller bandwidth than the final design. It was tested that swapping the two capacitors actually enhanced the reception of signals and resulted in a longer range. The drawback is that a larger bandwidth would allow the tone decoder to accept a wider range of signals in terms of frequency. It was concerned that the receiver could pick up more noise which could affect the reception of signals this way, but the experiments showed no serious problems with the "wrong" set-up of capacitors.

When the LM567 Tone Decoder finds a 40-kHz ultrasonic signal, it pulls its output pin (Pin 8) low, and the LED should light. The LED is a clear indication of whether or not the receiver catches an ultrasonic signal from the transmitter.

Similar to the beacon circuit, the receiver circuit uses the 5-V voltage regulator on the main board gain power. The output pin (Pin 8) on the LM567 Tone Decoder is connected

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[8] LM741 Op-amp Data Sheet: http://www.ti.com/lit/ds/symlink/lm741.pdf

[9] LM567 Tone Decoder Data Sheet: http://www.ti.com/lit/ds/symlink/lm567.pdf

to an I/O pin on the main board. The I/O pin is configured as an input pin so that it is able to detect signals from the LM567 Tone Decoder. When the output pin (Pin 8) on the LM567 Tone Decoder is pulled low, the main board knows that an ultrasonic signal has been received, and it stops running the counter and calculates the travel time of the signal.

It is important to set up a threshold value which can differentiate the high and low voltage of this I/O pin. If the threshold is too low, the main board may miss the detection of the signal and run the counter infinitely. Also, a low threshold may decrease the range of detection, which significantly limits the application of the whole system. However, if the threshold is set to high, it may be disturbed easily by some factors other than the ultrasonic signal. If this is the case, then the main board may mistakenly indicate the reception of the signal and stop the counter too early. Thus, it is critical to determine the threshold at the I/O pin to accurately indicate the signal reception. The optimal threshold value can be experimentally determined by measuring the voltage at the output pin (Pin 8) on the LM567 Tone Decoder. It is easier to adjust the threshold value in the code instead of altering the hardware, so it was handled primarily by the Programming Team for the project.

## 3.3 Final Product

A quick recap of the logic of receiving an ultrasonic signal is presented below, assuming Pin B6 (I/O pin) is used to receive a signal from the receiver circuit:

(1) The receivers (transducers) pick up an ultrasonic signal and start vibrating, generating an periodic voltage signal.

(2) This signal is amplified by the LM741 Op-amp while the frequency is maintained.

(3) The amplified signal is fed into the LM567 Tone Decoder. The tone decoder compares the frequency of the signal with its internal frequency, which is set to 40 kHz.

(4) If the frequency of the signal is close to 40 kHz, within the bandwidth set by the capacitors on Pins 1 and 2 of the tone decoder, the tone decoder pulls its output pin (Pin 8) low and lights the LED.

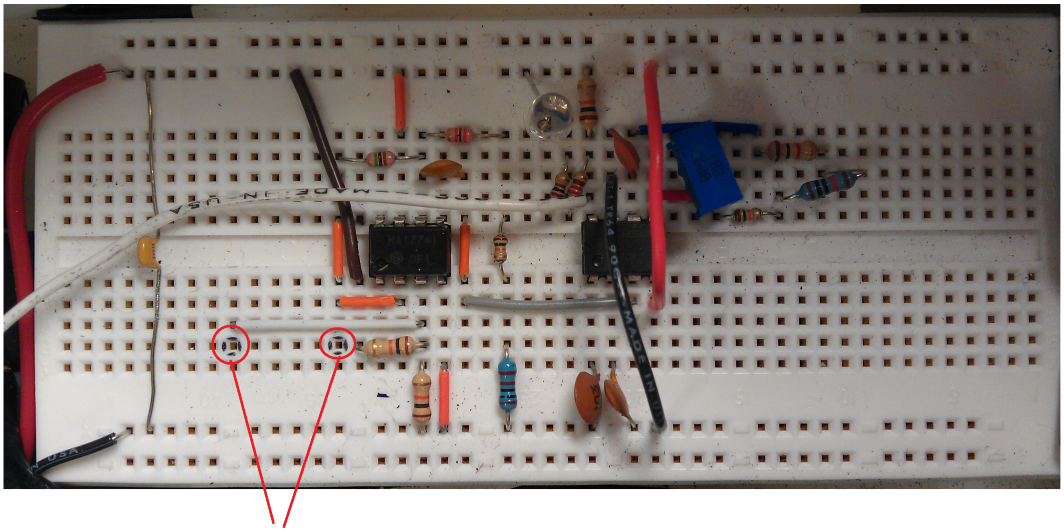
(5) Pin B6 on the main board receives a low input, and it recognizes it as a reception of the ultrasonic signal. The counter on the receiver stops running. The travel time of the ultrasonic signal from the beacon to the receiver is calculated based on the number of timer counts.

A detailed view of the receiver circuit without the main board is illustrated by Figure 6. An additional capacitor was added in the final receiver circuit across ground and live (+5 V from the voltage regulator). The purpose of adding this capacitor was to reduce noise. A 0.1-$mu$F capacitor reduces high frequency noise, and a 10-$mu$F capacitor reduces low frequency noise. A 0.1-$mu$F capacitor was selected for this application.

# 4 Transducer Arrangement

This section presents the arrangements of transducers on both beacons and receivers. The major challenges of arranging the transducers were:

(1) One pair of transmitter and receiver would not be sufficient to cover the playing field due to the beam pattern. An intuitive solution was to use multiple transducers to increase the



Connect to Transducers

Figure 6: A Detailed View of a Receiver Circuit without Main Board

range. How should multiple transducers be held together to produce the optimal coverage?

(2) Are the beacon and receiver circuits able to power multiple transducers simultaneously? Will it affect the performance of individual transducers?

## 4.1 Beam Pattern

The beacon circuit and receiver circuit were tested using one single ultrasonic transducer on each in order to estimate the range of the signal. The transmitter and receiver used on the prototype boards were 400ST160 and 400SR160 [10], respectively. When using only on pair of transmitter and receiver to transfer signals, the coverage was limited due to the beam pattern of the transducers. The data sheet of the transducers provides a beam angle measured at 40 kHz.

The actual beam pattern was obtained experimentally in the North Dome of Edmund P. Joyce Center (JACC) at the University of Notre Dame. This location was chosen because it has a similar structure as Stepan Center, where the final game took place. The supply voltage on the beacon board was 12 V as opposed to 36 V.

A series of distance marks were made along a straight line on the ground. Both the transmitter and receiver were set at the same height of 22 inches above the ground. The transmitter was located at the origin of the line, and the receiver was moved gradually from the origin. The main boards were not used in this test. The transmitter was sending a consistent ultrasonic signal during the test. The LED in the receiver circuit indicated whether or not a signal was received while the receiver was moved along the line.

Three sets of tests were conducted. The first set was conducted with the transmitter facing directly towards the receiver. The second set was conducted with the transmitter

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[10] 400ST/R160 Transducers Data Sheet: http://www.farnell.com/datasheets/81163.pdf

rotated 15 degrees away from the straight line on the ground on both left- and right-hand sides. The third set was conducted similar to the second one, but the angle was 30 degrees.

By varying the distance and angle between the transmitter and receiver, a coverage pattern was obtained and is illustrated by Figure 7. When the receiver was facing the transmitter, the maximum distance that a signal could still be picked up was 40 ft. When the angle between the receiver and the transmitter was increased, the maximum distance dropped down. When the angle was 15 degrees, the maximum distance was 35 ft. When the angle was 30 degrees, the maximum distance was 30 ft.

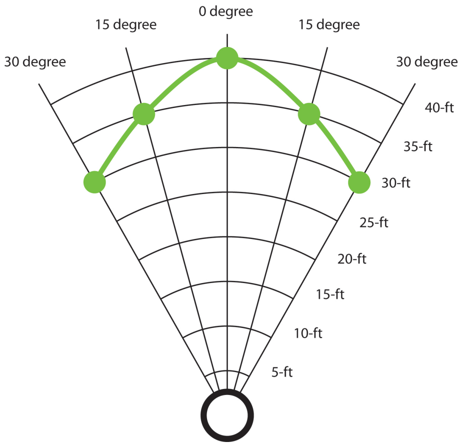


Figure 7: An Illustration of Coverage Pattern with 12-V Supply Voltage on the Transmitter

The maximum distance was the range that the transducers could cover. It was assumed that by using a higher supply voltage, the distance range could be increased to 50 ft, while the beam pattern stayed the same.

One important observation from the tests was that the transmitter and receiver must be on the same horizontal plane. Any vertical difference or tilt between their positions would significantly reduce the signal range. Therefore, the transmitters and receivers should be mounted at the same height, preferably close to the maximum allowable height (24 in), in order to avoid potential barriers between the beacon and receiver.

In order to increase the angular range, the beacon circuit and receiver circuit both have the ability to control multiple transducers simultaneously.

## 4.2 Transducer Housing

To firmly hold multiple transducers in place to attain the desired coverage, a set of ultrasonic transducer housing made of 1/2”-thick high-density polyethylene (HDPE) was fabricated on the CNC machine. Since each transducer has a beam angle about 60 degrees, theoretically, six transducers should be enough to cover 360 degrees. To ensure better coverage, the housing has eight slots to hold eight transducers together to cover 360 degrees. Figure 8 illustrates the CAD model of the transducer housing in Pro Engineer. The left half of the figure is the complete view of the housing. The top portion is hidden in the right half of the figure to indicate the positions of the transducers. In the application, not all eight slots were used due to a lack of transducer supply in supplier's inventory.

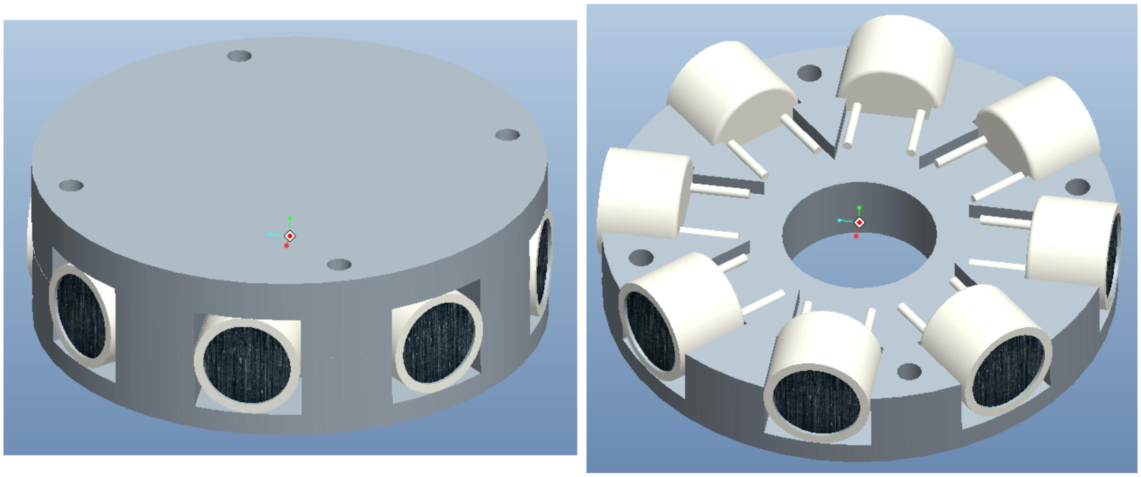


Figure 8: CAD Model of an Ultrasonic Transducer Housing

## 4.3 Arrangement on Beacon

In Figure 2, the beacon circuit has four identical lines in parallel to power four transmitters separately. By duplicating those lines, more transmitters can be added to the circuit. The three 12-V SLA batteries can supply enough current to power multiple transducers, which do not consume that much electric energy. Only four transmitters were used on each beacon because the beacons were positioned around the robots. The beacons did not need to cover 360 degrees. Figure 9 illustrates the positions of the three beacons and the coverage of the system, with a range of 50 ft between transmitter and receiver. The three little circles in red, blue and magenta represent three independent beacons. The three large semicircles with the same colors indicate the coverage of the beacons correspondingly. The cyan straight line across the field represents the line of scrimmage. The green rectangle indicate the area in which the Quarterback and two Wide Receivers may be on the field. Figure 9 demonstrates that the green rectangle is well covered by all three semicircles. As long as the robots have the ability to receive signals in the green rectangle, the system should work well in this region. Thus, using beacons with an angular range of 180 degrees should be sufficient for this application. Theoretically, three transmitters should be able to cover 180 degrees. Due to the limited number of transmitters available, four transmitters were used to attain a slightly enhanced coverage. Figure 10 illustrates the actual arrangement of transmitters on the beacon. Since each transmitter is controlled by a corresponding TN0103N3 Transistor, the transmitters are independent of each other. They can share the same ground wire, but each one should have its own live wire to the corresponding transistor.

Each transducer has two leads, and they are not the same. On the back of the transducer, one lead has a little circle around it and the other one does not. Figure 11 illustrates this small difference. When soldering wires to the two leads, make sure to use different colors to

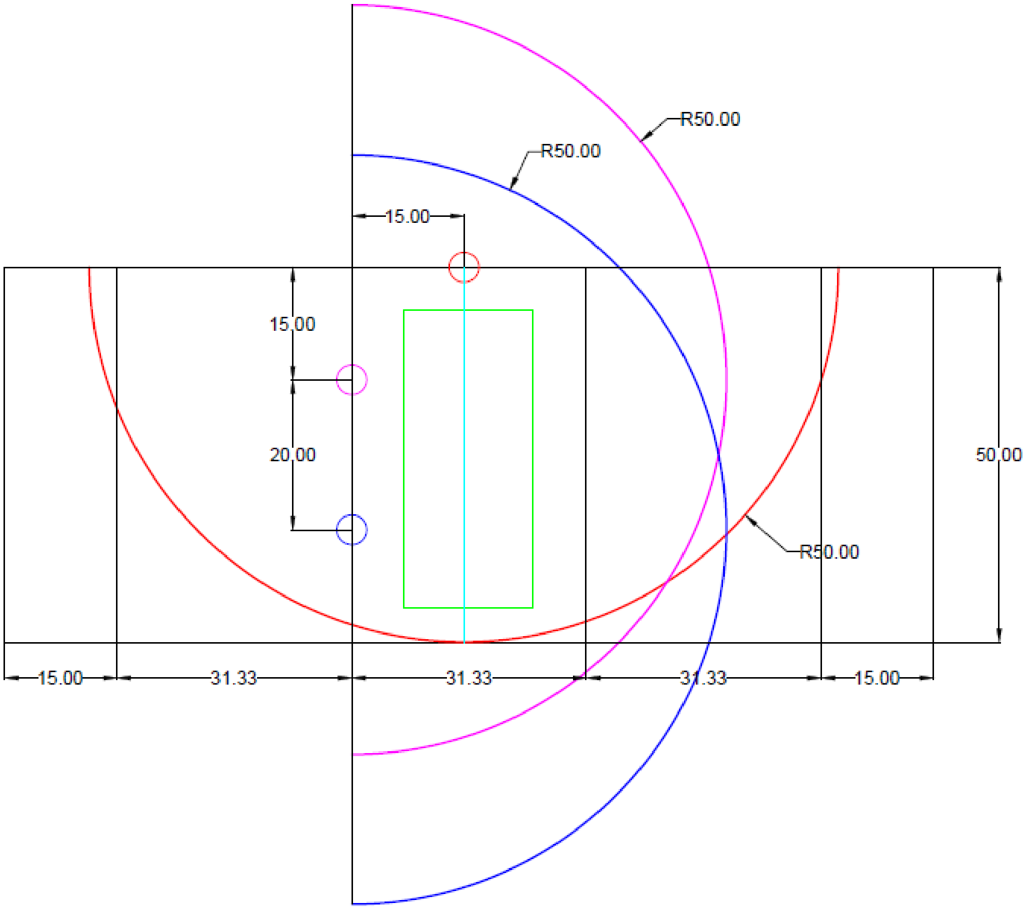


Figure 9: An Illustration of Coverage on the Playing Field (Unit: ft)

distinguish this difference. The heat shrink around the wire and lead would make the small mark invisible. Since the transmitter is independent from each other, this difference will not make a huge impact for signal generation. However, it would have a serious impact on the receiver if the two leads were not differentiated.

50 ft was the maximum range that could be attained, so the beacons had to be moved along with the line of scrimmage instead of completely stationary. How beacons were made to be mobile will be discussed in Section 5.

## 4.4 Arrangement on Receiver

In order to eliminate potential confusion, following definitions are used: A transducer refers to an ultrasonic receiver as opposed to a transmitter, though both transmitters and receivers can be called transducers. A receiver refers to a system which includes the transducers and the receiver circuit. A Wide Receiver refers to a mechatronic football player.

Similar to what have been shown in Figure 8 and 10, each receiver consists of a housing

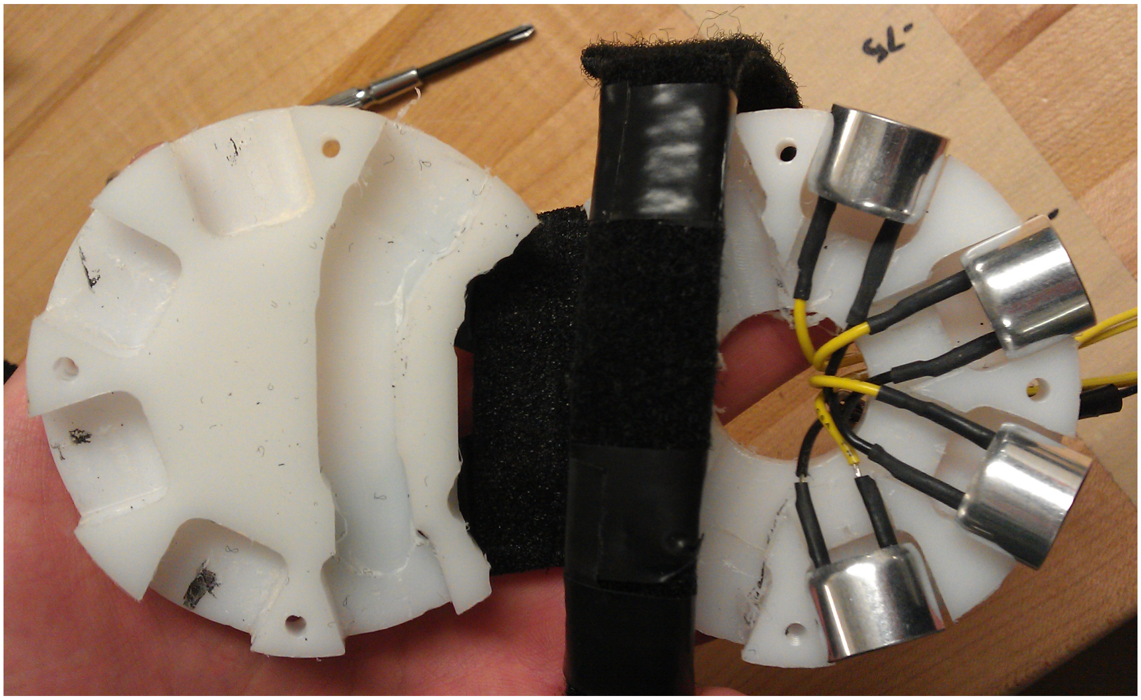


Figure 10: Arrangement of Transmitters on the Beacon

Figure 11: Difference between Two Leads on a Transducer

and multiple transducers. The Quarterback has seven receivers (transducers), and each Wide Receiver has five. Using multiple transducers increases the angle at which a receiver is able to pick up an ultrasonic signal. The Quarterback has an angular range of at least 315 degrees. Each Wide Receiver has an angular range of at least 225 degrees. Ideally, eight transducers should be used on each receiver to make it omni-directional. Due to the limited supply of transducers, the number had to be reduced.

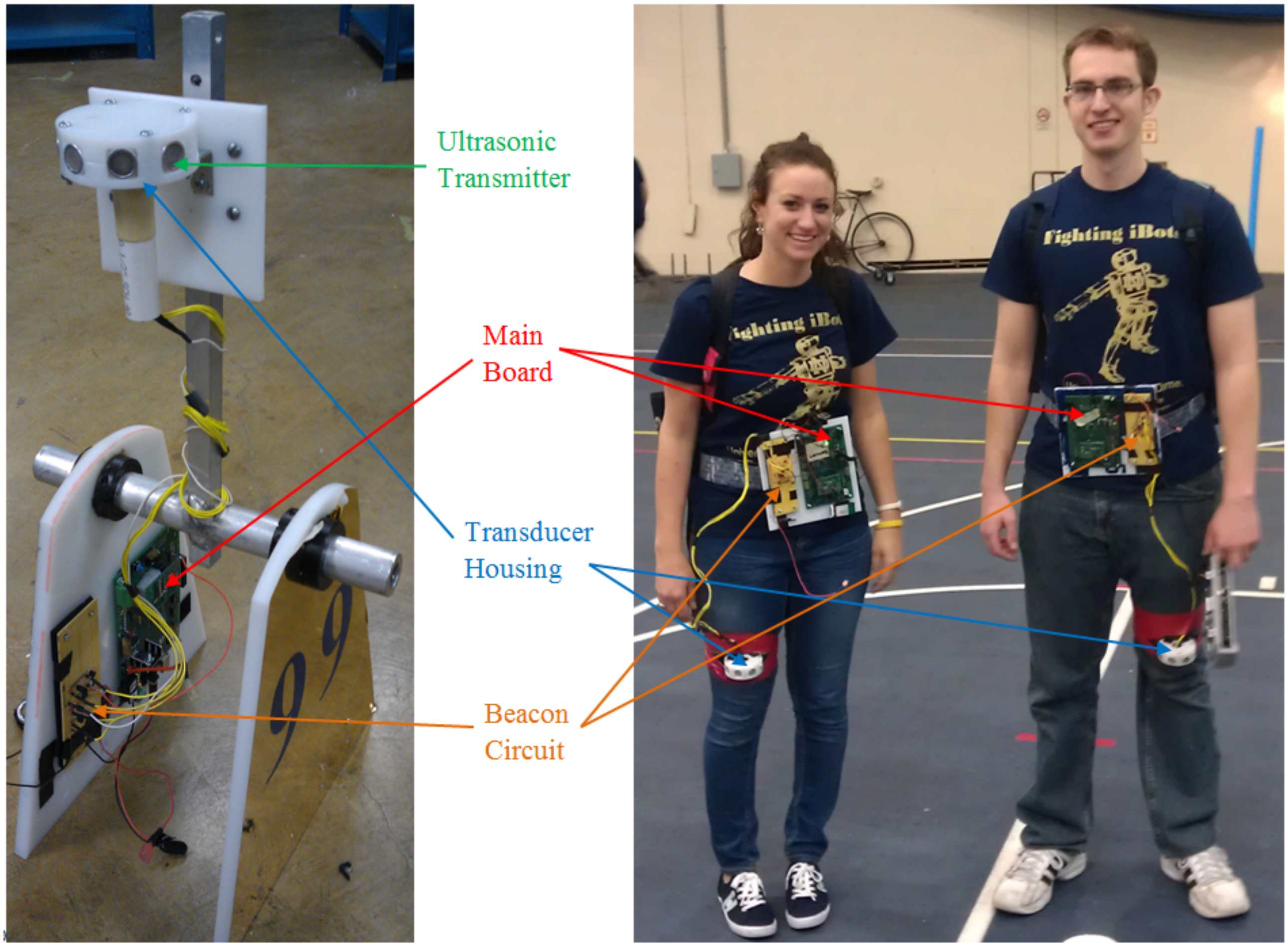
The connection of the transducers are different for receivers. Unlike the transmitters on each beacon, the transducers on each receiver are connected in series. It was noted in Section 3.2 that the voltage signals produced by each transducer should be in phase. Since each transducer has two different types of leads, one lead cannot be connected to another lead of the same type, otherwise the signals from two connected transducers would be out of phase and cancel each other. Always use color-coded wires when making serial connections with the leads.

# 5 Installation

This section presents the installation of a sideline beacon and two human-mounted beacons as well as the receivers on the robots.

## 5.1 Sideline Beacon

The sideline beacon is indicated by the small red circle in Figure 9. Part (1) in Figure 12 illustrates the sideline beacon without batteries. In order to achieve the optimal coverage, all the transducers were mounted at a height of 24 inches, which was the maximum allowed by the rules. The major structure of the sideline beacon was recycled from last year's kicker. The transducer housing is mounted to a thin piece of HDPE. It is critical to ensure that the housing is leveled, so that the transmitters are pointing horizontally. Four yellow wires and one black wire were used to connect the transmitters to the beacon circuit. Three 12-V SLA



(1) Sideline Beacon

(2) Human-mounted Beacons

Emily Gore Matthew Nagy

Figure 12: An Illustration of (1) Sideline Beacon and (2) Human-mounted Beacons

batteries sit on the floor and are connected to the beacon circuit to power the transmitters. During the game, the sideline beacon along with the batteries were moved with the line of scrimmage.

## 5.2 Human-mounted Beacons

Part (2) in Figure 12 illustrates the human-mounted beacons worn by Emily Gore and Matthew Nagy, two members of the Mechatronic Football Project Team, who controlled a Wide Receiver and the Quarterback, respectively, during the game. The equipment is essentially the same as that on the sideline beacon, as shown in Figure 12, but the installation was more complex. Since the beacon circuit and the main board are relatively fragile, particular attention have to be paid to maintain their functionality. After careful consideration, it was decided to mount the beacon circuit and the main board on a piece of HDPE with bolts and nuts, and attach the HDPE to human bodies with Velcro fasteners. The Velcro fastener was made into a belt and were permanently attached to the back of the HDPE, and the human controllers wear it as a belt, which can be easily adjusted based on the size of the body. There is a piece of foam and a sheet of insulation paper between the beacon circuit and the HDPE board to protect the soldered connections on the back of perfboards. With the beacon circuit and main board in the front, the human operator can constantly monitor the conditions of the two and make sure they are not damaged.

The Velcro fastener was also used to secure the transducer housing. The transducer housing needed to be mounted at 24-in above the ground, which is right above the knees. It was very difficult to maintain the level of the transmitters, since they were supposed to stay horizontal. The Velcro fastener alone was able to hold the transducer housing in place, but not to secure the transmitters' level. Thus, duct tape was used to strengthen the connection. The level of the transmitters also depends on the position of the legs. It is critical that the human operators maintain the same pose while the ultrasonic signals are being transmitted. Future teams should device a means of keeping transmitters level on humans to improve consistency of signals.

The transmitters on the human-mounted beacons were also powered by three 12-V SLA batteries in series. In order to limit the length of the wires and improve the mobility of the beacons, the batteries were put in a backpack with two wires sticking out to connect to the beacon circuit. Extra care was required to keep the three 12-V SLA batteries from shorting. Thick gage female crimped terminals were used to connect batteries with wires.

How should the human-mounted beacons be installed? Assume that the transmitters are permanently attached to the beacon circuit and the beacon circuit is properly connected to the main board.

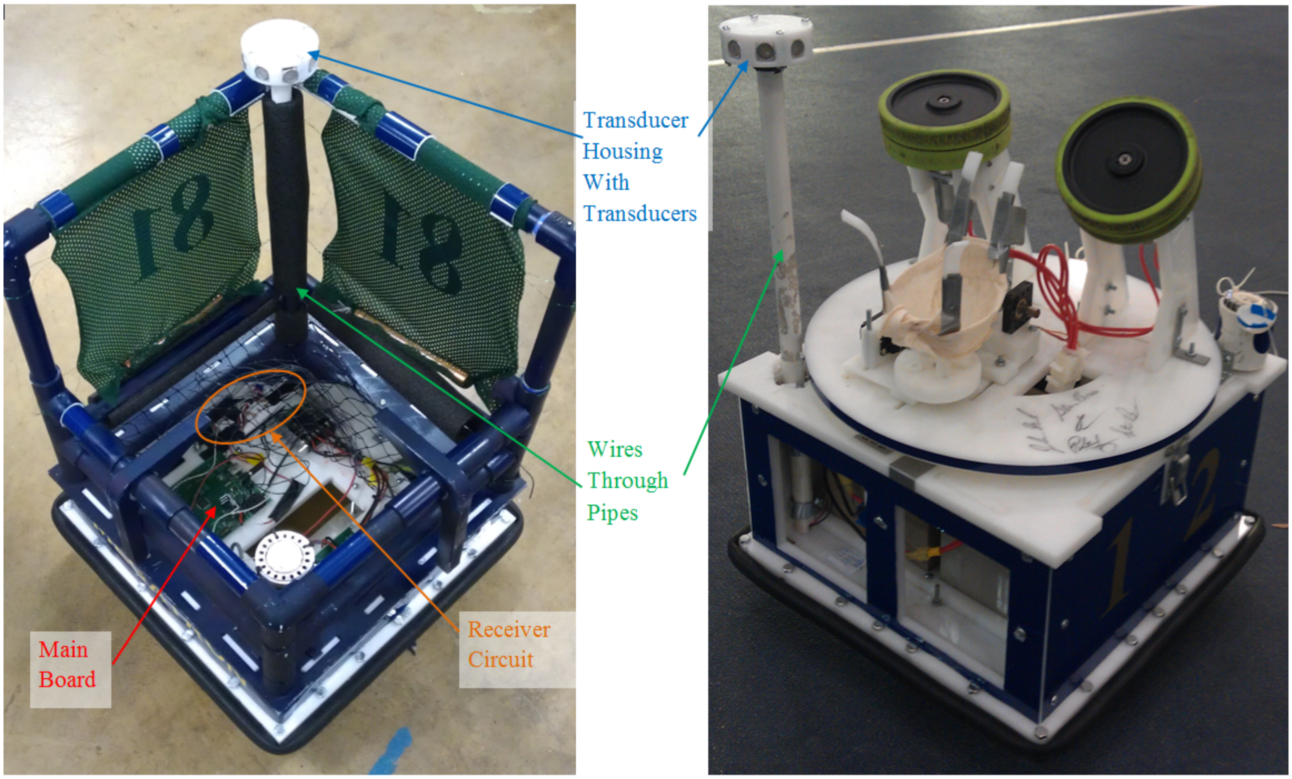
*Step 1*: Put on the HDPE and secure the Velcro fasteners around the waist.

*Step 2*: Put on the transducer housing and secure the Velcro fasteners right above the knee. Use a scale/measuring tape to ensure that the transmitters are 24 in above the ground. Use duct tape to strengthen the connection and adjust the direction of the transmitters.

*Step 3*: Put on the backpack with three SLA batteries. Connect the batteries to the beacon circuit. Connect the main board to a 9-V battery.

## 5.3 Receivers

The receivers were installed on the Quarterback and two Wide Receivers. The biggest difference between the beacon and receiver systems is that the receiver system does not require 12-V SLA batteries. The receiver circuit is powered by the 5-V voltage regulator on the main board, and the transducers connected to the receiver circuit also share the same power supply. Figure 13 illustrates the receivers on the Wide Receiver Megatron and the Quarterback Sleepy Jim. The Wide Receiver Michael Droyd had the same set-up as Megatron. The receiver circuit was placed close to the main board for easy connections.



(1) Wide Receiver Megatron

(2) Quarterback Sleepy Jim

Figure 13: An Illustration of Receivers on (1) the Wide Receiver and (2) the Quarterback

The receiver circuit on the Wide Receiver is circled in Figure 13. The receiver circuit on the Quarterback is mounted behind the main board on one side of its chassis. The wires connecting transducers to the receiver circuit go through a PVC pipe, which is firmly mounted on the robot.

Though perfboards were used to build the beacon circuits, two of the receiver circuits were built on bread boards for game day. The components were soldered to the perfboards, while the components on the breadboards were simply plugged into the sockets. The perfboards were thus considered more reliably than breadboards. However, the perfboards had brought consistent trouble to the receiver, so two new receiver circuits had to be built on breadboards two days before the game. The issues with perfboards will be discussed in detail in Section 6.

Due to the time constraint, the two receiver circuits built on breadboards were mounted onto the robots using electric tape. The connections were sufficiently strong to hold the circuits in place while taking impacts from other robots during the game. However, it would be better to replace the electric tape with more reliable connections. The receiver circuit on Wide Receiver Michael Droyd was built on a perfboard, and it remained functional throughout the game. The circuit was bolted onto the robot and there is also a piece of foam and a sheet of insulation paper under the perfboard.

# 6 Issues and Recommendations

## 6.1 Inconsistency of the System

It was experimentally determined that each pair of transmitter and receiver could generate and receive ultrasonic signals within 50 ft consistently. However, when multiple transducers were implemented, sometimes the system still did not work as well as expected. The main boards on the robots had trouble getting reasonable distance measurements based on the travel time of signals. This issue was supposed to be carefully investigated, but there was no time for a comprehensive troubleshooting before the game.

One possible explanation would be that there were not enough transducers on each receiver. The Quarterback had seven transducers on board, which should have better signal reception than a Wide Receiver, which only had five transducers. If the robot were not facing all three beacons properly, one of the three distance readings would be off by quite a bit. Simply adding more transducers may eliminate this problem, but the supplier did not have enough transducers in stock.

Another possible explanation would be related to the trilateration code. As mentioned in Section 3.2, a threshold voltage value should be set in the code to identify the recognition of an ultrasonic signal. If the LED on the receiver circuit did not flash while a signal was being transmitted, the hardware might be problematic. If the LED on the receiver circuit flashed but the reading was way off, the threshold value in the code might be inappropriate. It is also possible that the hardware has some problems in this case which may affect the readings. It is highly recommended that the Electronics Team and the Programming Team can conduct a thorough investigation together next year to identify the actual problem. This is paramount for the success of the whole system. Another approach would be having the same team of people to be in charge of the overall system. Having a good knowledge in both hardware and software will be beneficial to the future development of the system. A separate-team approach is only better when developing the system from scratch. If the system will be used next year, the first task should be troubleshooting the system as a whole. The rest of the work is mostly reliability engineering.

## 6.2 Type of Ultrasonic Transducers

It is noticed that the 400ST/R160 Transducers used in this system are supposed to handle up to 20 V. However, the voltage across each transmitter is 36 V, which is far beyond the specified value. Some so-called ultra-long range ultrasonic transducers were purchased initially, but they did not work as well as the 400ST/R160 Transducers, which were obtained directly from Mr. Brownell. A manufacturer of the ultra-long range transducers provided some data on their products. If a transmitter and a receiver are placed face to face, the longest range that can be attained is about 40 m, or 131 ft, using 120-V supply voltage. The recommended supply voltage is 75 V. They did not specify the type of the power source, either AC or DC. Nevertheless, it was difficult to obtain a power source with such voltage, and it was not allowed by the rules. The 400ST/R160 Transducers were tested under 36 V and worked reasonably well in terms of range and reliability. Since it was too late to test more options, the 400ST/R160 Transducers were selected and implemented on the final system. If time and budget permitted, more options of ultrasonic transducers should be tested before finalizing the selection. Transducers that can provide longer range and wider beam angle are desired.

One inherent problem with the ultrasonic transducers is that their optimal frequency is mostly 40 kHz. If the ultrasonic signals from the beacons are not encoded, they have to be sent one by one, otherwise the receivers will not be able to tell where the signal comes from. However, in order to attain the optimal range, all the transmitters were run at 40 kHz. This characteristic of the ultrasonic transducers may limit the future development of the whole system.

## 6.3 Inconsistency of the Circuit Boards

The circuit boards constructed using simple components such as resistors, capacitors, integrated circuits and potentiometers exhibited a higher level vulnerability and inconsistency beyond expectation. The development process could be divided into three categories of tasks: a) research and design, b) construction and installation, and c) troubleshooting and repair. The time allocated to each category was roughly 20%, 30% and 50%. Troubleshooting and repair were intensively time-consuming, which significantly slowed down the progress of the development. Often times a component on the circuit board became dysfunctional for unknown reasons, and it might take several hours to detect and fix the problem. The limited knowledge in electronics that most Mechanical Engineering majors had was far from adequate to resolve the problems in an efficient manner.

The components that have failed during tests were: the LM741 Op-amp, the LM567 Tone Decoder, the potentiometer, breadboards and perfboards. The op-amp and tone decoder went bad for unknown reasons. The easy solution is to replace them with new ones, but the problem is so subtle that it may take hours to identify the problem. Checking the output from each pin using an oscilloscope would be a good idea for troubleshooting. The potentiometer might be over tuned and could not maintain the resistance any more. It should be avoided to tune the potentiometer repeatedly. There are a lot of sockets on the breadboards, which is easier for connections. However, if a wrong gage lead or wire is plugged into a socket, the socket may be enlarged and result in a loose connection if a smaller gage lead is plugged in later. This is also a very subtle problem and requires an oscilloscope for troubleshooting.

The perfboards were considered a more reliable option than the breadboards, simply because all the components should be soldered on. Unfortunately, the specific perfboards purchased and implemented caused the most trouble. If a component was broken, it had to be desoldered from the perfboard. The perfboards usually have copper lines on the back to make the connections. When a component is desoldered from the perfboard, it may take the copper off as well, which results in a broken connection in that line. It is difficult to use solder to fix the connection, though it might be the most intuitive solution. Another disadvantage of using perfboards is that they are sensitive to bending. The receiver circuits had to be mounted on the robots, which did not have holes drilled for putting in bolts. When the holes were not perfectly drilled, the perfboard might subject to a bending force which changed its shape slightly. However, this slight change would result in detrimental effect on the circuits. It was observed that the receiver was perfectly working before being mounted on the Quarterback, but after it was in place, it was no longer working properly. Pressing the perfboard slightly to reduce its deformation due to mounting, the perfboard became normal again. All the connections were fine during before and after this test, so the bending might be the only factor that caused the problem. Thus, the receiver circuits made on perfboards were replaced by those made on breadboards. It is recommended to keep using breadboards for self-designed circuits, assuming they are well constructed and maintained. Using a more expensive option of perfboards may be a good idea as well, but it is uncertain whether they will be affected by the bending or not.

## 6.4 Type of Batteries

Using three 12-V SLA batteries is really unnecessary, considering the low power consumption of the beacons. They were used anyways because it was difficult to find a replacement which could also generate 36 V. A couple 7.2-V batteries in series might be a solution, but no time could be spent on further investigating this possibility due to the unique type of connections used by such batteries. Smaller 12-V SLA batteries should be available to purchase online, but the budget was tight and there was not enough time for shipping. It is definitely recommend to replace the three 12-V SLA batteries with something lighter and smaller next year to reduce the weight carried by human operators.

The receiver circuit is entirely powered by the 5-V voltage regulator from the main board. In order to improve the gain value on the op-amp, a higher voltage source may be adopted to power the op-amp independently, avoiding the connection with the main board, which cannot handle a voltage higher than 9 V. A 9-V battery was tried to power the op-amp before, but there was no significant improvement. A higher voltage may be tried next year.

## 6.5 Type of Main Boards

The same type of main boards have been used for several years throughout the history of the Mechatronic Football Game. The Programming Team had to deal with the main boards frequently and they will describe the problems in further details.

The major trouble that the main boards caused for the ultrasonic positioning system is that they do not have sufficient memory on board to store more data points. Each travel time of the ultrasonic signal was calculated on one sample, which was not enough to identify and eliminate the outliers to improve the consistency of the acquired data. The Programming Team sometimes had trouble getting reasonable readings from the system. If one reading was bad, the positions would not be determined accurately. Ideally, more data points should be taken from each beacon and the outliers should be eliminated before computation, but it may exceed the capability of the main boards.

During the test, it is noticed that the main boards consumed the 9-V batteries quickly. If the 9-V battery is low, it is not able to power the main board properly. The beacons may not be able to generate ultrasonic signals, and the receivers may not be able to pick up the signals. The little green LED on the main board may be used to monitor the battery level, but it is not a reliable indication since the intensity of light only changes subtly when the battery level is low. If the same type of main boards will be used next year, the operators should be aware of this issue.

## 6.6 Other Issues

The ultrasonic positioning system can only determine the positions of the robots on the field. Their orientations should be determined separately, unless the Quarterback is always facing forward. The Programming Team tried to implement a digital compass on the Quarterback and Wide Receivers to determine their orientations, but it was not successful. The inaccurate information on orientations may result in a wrong adjustment of the turn table on the Quarterback, and the pass is unlikely to be completed. Implementing digital compasses is highly recommended to obtain information on orientations.

One of the ultimate goal of developing the ultrasonic positioning system is to run the robots autonomously along pre-defined routes, which will require some sort of positioning feedback for each robot. The current system has to send the signals one by one from each beacon, which prevents the system from determining each robot's position instantaneously. It may be possible to provide feedback not so frequently. One or two times during each second should be sufficient. However, the robots are generally moving very fast. It is difficult to say whether a slow feedback would work well with such high speeds without conducting a quantitative analysis .

# 7 Conclusion and Outlook

The system was not totally completed until several days before the game. A few tests were conducted in the last week and several passes were completed. The huge remaining issues is that the system is not quite consistent yet, which should be investigated next year if the system will be used again. Passes relying on the ultrasonic positioning system were attempted during the game, but the Quarterback did not adjust the orientation of its turn table and the speed of its wheels as expected, so the human operator had to run the ball with the Quarterback or manually adjust the turntable and speed of throwing wheels.

If this were considered a product development project, the current progress would be around 50% to 60%. The problem causing the inconsistency of the system should be identified, followed by more reliability engineering work.

If the system were perfectly working as supposed to be, it would definitely create an advantage over manual passes. This is the major motivation of developing an intelligent system.

During the Critical Design Review, the Commissioner expressed some interests in sharing the system with another team, so both teams could use it as an indoor GPS system and focus on autonomous plays. This will reduce the amount of work for both teams, but it may also stagnate the promotion of the game across the country. Compared to improving drivetrain and chassis design, developing a positioning system is far more challenging. If such a system were shared by both teams, there would be much fewer challenging tasks confronted by the teams and fewer universities would be interested in joining the competition. Also, it is still uncertain how long it may take to improve the system to an adequate level.

# A Code in PIC12F510 Microchip

The following code was written by Mr. Brownell.

```
;PROGRAM SPIKE.ASM
;Rev. 0 4-5-2012
;crude timing using nop's as delays
;a better way exists

        list    p=12f510
        #include p12f510.inc

      __CONFIG    _CP_OFF & _WDT_OFF & _IntRC_OSC & _IOSCFS_ON & _MCLRE_OFF

;declare variables in RAM
        CBLOCK  0x0A
TempA   ;temporary storage buffers
TempB
TempC
TempD
TempE
Count   ;counter for BCD calculations
        ENDC

;==========================================================================
;program reset vector
        org     0
                movwf   OSCCAL          ;trim internal osc
        goto    main
;==========================================================================
Init_AD
        movlw   B'00000000'     ;turn ADC off
        movwf   ADCON0          ;INTOSC/4
        retlw   0

Get_AD
        movlw   .125
;       call    Wait                    ;settling time delay
        bsf     ADCON0,GO               ;start conversion
w2c
        btfsc   ADCON0,GO       ;A/D done?
        goto    w2c             ;no then wait
        retlw   0

Delay
```

```
                bsf             STATUS,5
                movlw   .255
                call    Wait
                goto    done_delay

Wait    ;time delay function
        movwf   TempB
mWait
                movwf   TempC

Next
        decfsz  TempC,f
        goto    Next
                decfsz  TempB,f
                goto    mWait
done_delay
                bcf             STATUS,5
        retlw   0

main
        movlw   B'01000000'
        movwf   CMCON0
        call    Init_AD
        movlw   0x08            ; all outputs except GPIO3
        tris    6
        movlw   0x0
        OPTION
        movlw   0x0
        movwf   GPIO            ; clear outputs

loop

        movlw   0x3F
        movwf   GPIO
        nop
        nop
        clrf    GPIO
        nop
        nop
        nop
        nop
        nop
        nop
        nop
        nop
```

```
        nop
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        nop

shutdown
        btfss   GPIO,3           ; check enable pin
        goto    shutdown
        goto    loop

        END
```

# B First Design of Beacon Circuit

Figure 14 illustrates the circuit diagram of the first design of beacon circuit, which was modified based on the circuit diagram found on ECELab [11]. The major problems with this circuit design are:

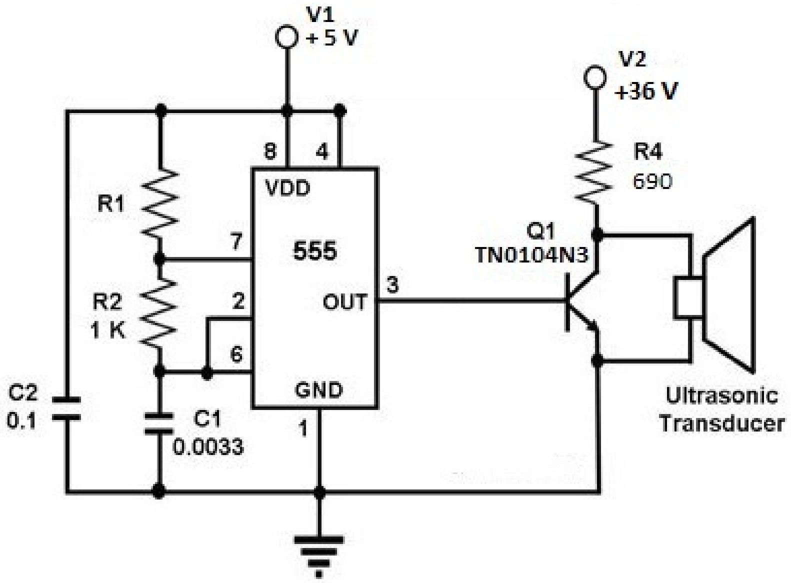

Figure 14: Circuit Diagram of the First Design of Beacon Circuit

(1) It uses a combination of resistors to set up the frequency for the LM555 Timer, which controls the frequency of the transmitters. It is difficult to manipulate the duty cycle of signals using hardware.

(2) The output pin (Pin 3) on the timer is difficult to control, which results in high power consumption by the resistor connected in series with the transmitter. High power rating resistors were used to handle the large current through the circuit when the transmitter was shorted by the transistor, but such resistors also introduced extra impedance to the circuit which was not desired.

Detailed explanation of the circuit is not provided here in order to avoid unnecessary confusion. The final design presented in Figure 2 is far more superior because the frequency can be easily adjusted by modifying the code and it has no problem with high power consumption. Thus, the circuit design in Figure 14 is not recommended for this application.

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[11] http://ecelab.com/circuit-ultrasonic-t.htm

# C Final Version of Beacon Circuit

Figure 15 illustrates the final version of the beacon circuit, including the main board.

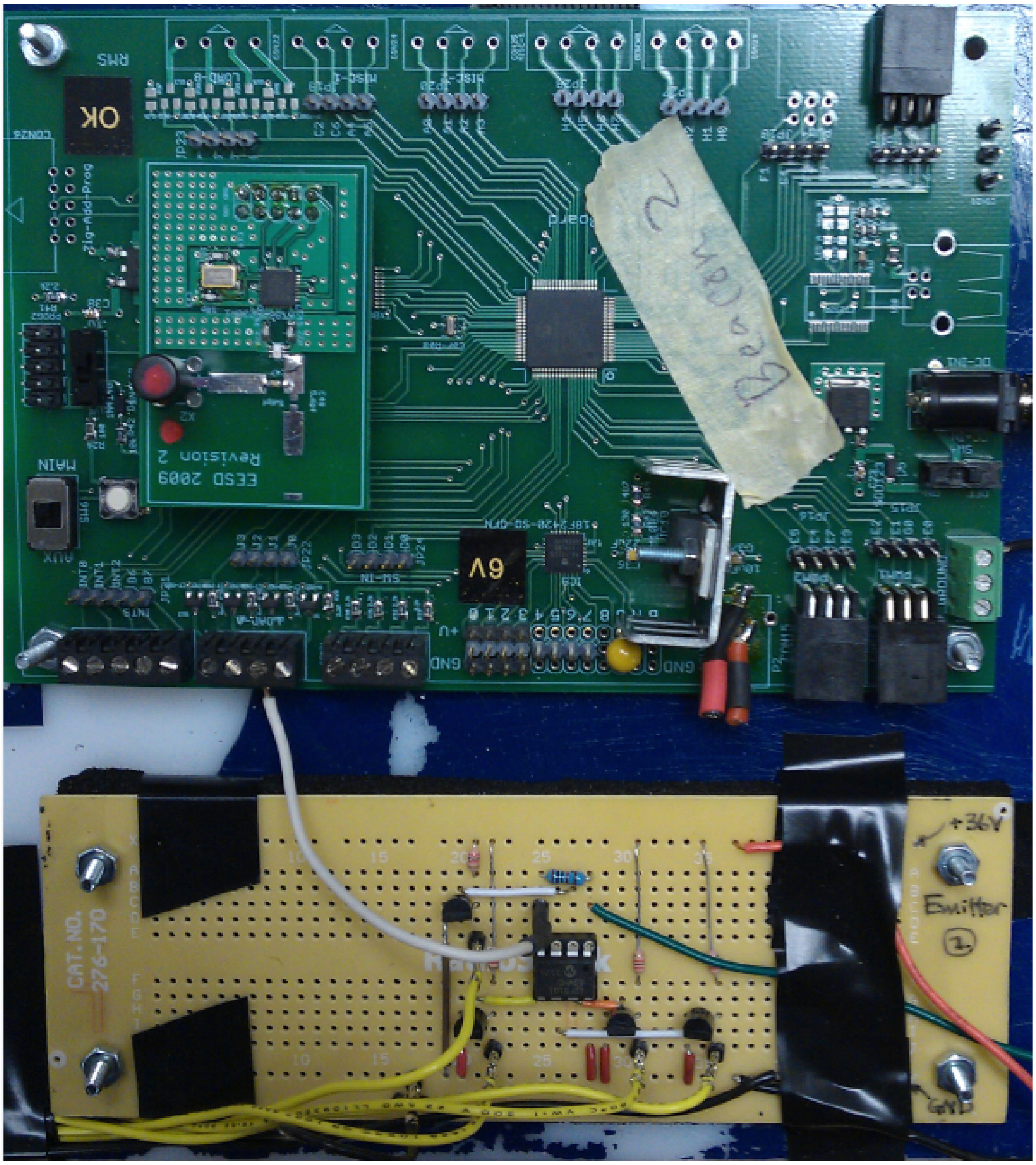

Figure 15: Final Version of Beacon Circuit with Main Board