Portable Sport Boundary Sensors

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ECE 445 Design Review – Spring 2017
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Table of Contents

1. Introduction…………………………………………………………………..……………3
    1.1 Objective…………………………………………………………………...…3
    1.2 Background………………………………………………………………....3
    1.3 High-Level Requirements…………………………………………………..…3

2. Design……...……………….…………………………………………………….…4
    2.1 Power Module……………………………………………………………………9
        2.1.1 Battery Charging Circuit …….……………………………………..……9
        2.1.2 12/5 V DC-DC Converter…………………………………………...9
        2.1.3 12/3 V DC-DC Converter…………………………………………...9
        2.1.2 Ni-Cd Battery……………………………………………………………10
    2.2 Detection Module…………………………………………………………………10
        2.2.1 IR Emitter…………………………………………………………...7
        2.2.2 IR Receiver…..………………………………………………...…8
        2.2.3 Hit Detection…………………………………………………………...8
        2.2.4 Ball Leg Detection……………………………………………………..8
    2.3 Display Module…………...…………………………………………………10
        2.3.1 Battery Level LEDs……………………………...………….…10
        2.3.2 Microcontroller……………………………………………….....10
        2.3.3 Display LEDs……………………………………………………………10
        2.3.4 Central Receiver………………………………………………….....10
    2.4 Risk Analysis………………………………………………………………...11

4. Ethics and Safety…………………………………………………………………………12

5. Reference……………………………………………………………………………...13

1. Introduction

1.1 Objective

Imagine yourself playing tennis and the game is starting to get very close. You're getting paranoid that your opponent is starting to call a few of your shots incorrectly which causes arguments in the match that can affect your gameplay. Our goal is to create a sensor system that would sense whether a shot is out or in and inform the players through LEDs.

There will be two sensors: an IR Emitter and an IR Receiver that will detect balls that land close to the line and determine if any part of the ball has touched the line or not. The sensor system will be easy to install, portable, able to withstand wind and water. This sensor system will be sturdy enough to withstand getting hit by a player or stepped on. The current plan is to have the sensors be battery-powered but if we have additional time we will try to make them solar powered. The sensors will be able to work on both indoor and outdoor courts. This project will benefit recreational and competitive sports as it will remove the tensions that line calls provide during games as well as allow the players to pay more attention to the game itself instead of lines.

1.2 Background

In professional tennis, there exists a very expensive Hawk-Eye Systems that tracks if the ball is in or out. Hawk-Eye started to be used professionally at the 2006 US Open. Its estimated cost for one court is approximately $65,000 [1]. However, in recreational play, there is no system that is used for determining if a ball is in or out. In the past, systems have used pressure sensors, video cameras, and magnetizing tennis balls to detect currents. These systems lacked portability and affordability. This sensors system will be relatively cheaper the alternative advanced camera technology. Using a system of advance cameras requires six cameras to be place aerially around the court. The images from all six cameras are used to determine if a ball is in or out. This is the system currently used at professional tennis tournaments. Looking at the price of the cheapest camera that could work for this arrangement, this system would run at about $2000, and that's for just the cameras.

1.3 High-Level Requirements

- Timing: The system should be able to display if the ball is in or out within 5 seconds of the ball breaking the beam.
- Accuracy: The system must detect if the IR beam is broken by a ball 90% of the time.
- Wireless: The system should be able to connect wirelessly on one network with multiple devices and detect the status of the connection.

2. Design

The portable sport boundary sensors will have three main modules to meet the requirements: a power supply, a detection block, and a display block. The power supply allows the system to be powered throughout it use through rechargeable a Ni-Cd Battery. We will be designing two DC/DC converters to step down the voltage to be used for our sensor design. Our detection block consists of our IR sensors, analog integration and amplification circuitry, and a microcontroller. These components process the sensor data and generate an output. The output block consists of four sets of LEDs, one for displaying the battery level, one for displaying wireless status, and one for displaying whether or not the ball hit the line, and one for detecting if the IR emitter and receiver are paired. Furthermore, we will be using a TRM-315-LT wireless transceiver to transmit data from the individual receivers to the central receiver device.

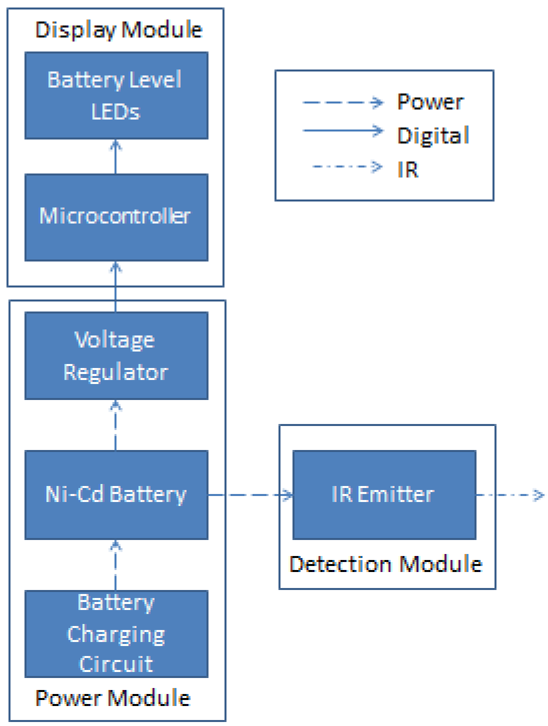

Figure 1: Emitter Block Diagram

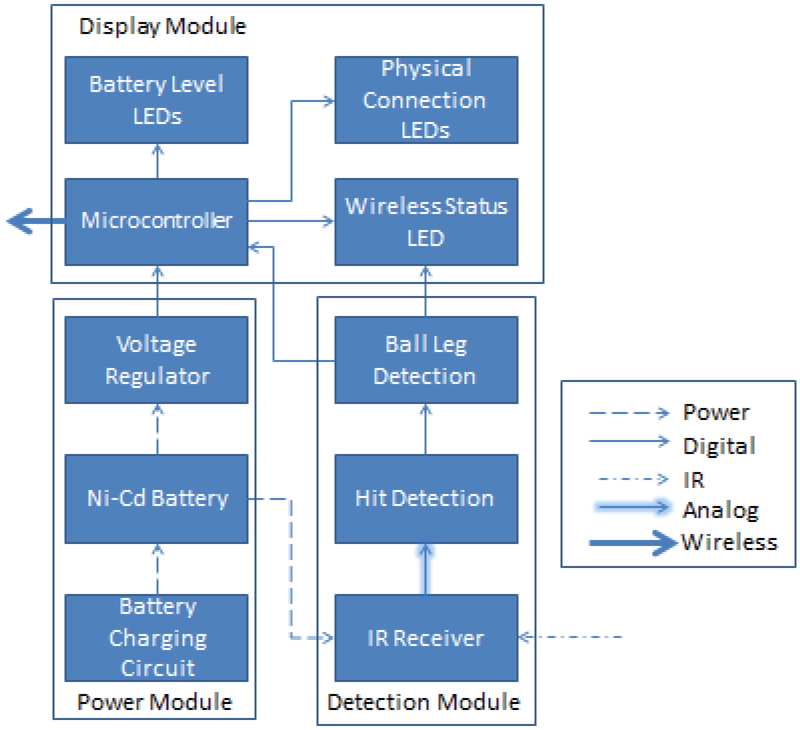

Figure 2: Receiver Block Diagram

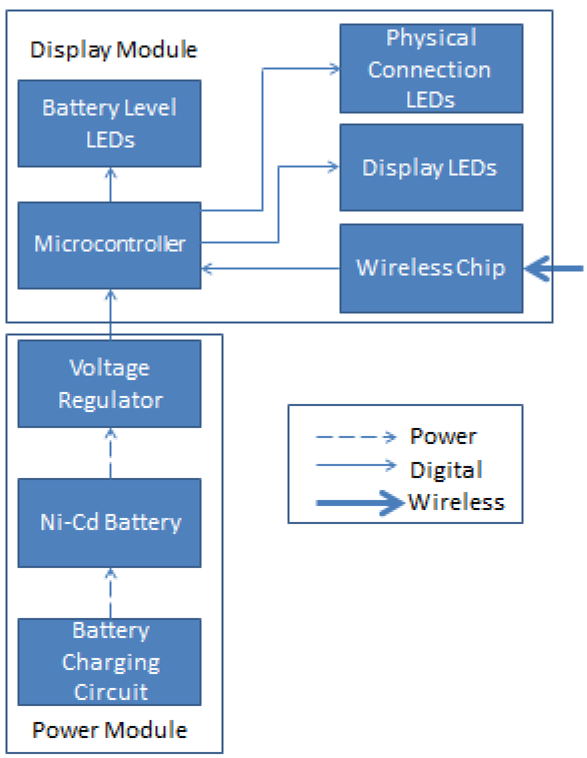

Figure 3: Central Receiver Block Diagram

Figures 4, 5, and 6 are proposed configurations of the sensor boxes for the emitters, receivers, and central receiver. The boxes will be sturdy so nothing is damaged if accidentally stepped on. Each box will have a pairing LED, blue, to notify users that the sensors are paired with each other and the central receiver. The LED will be on top of the boxes so users can easily see if any of the sensors of unpaired during play. The central receiver will have a cluster of red LEDs on top to notify users when a ball has been detected as out. The on/off buttons for the box and for pairing will be on the sides of the boxes. There will also be markings on the bottom edges of the box so users can properly align boxes on the court. Figure 7 is a half-court and more accurate visual description of the sensor arrangements from Figure 8, which is a full court visual.

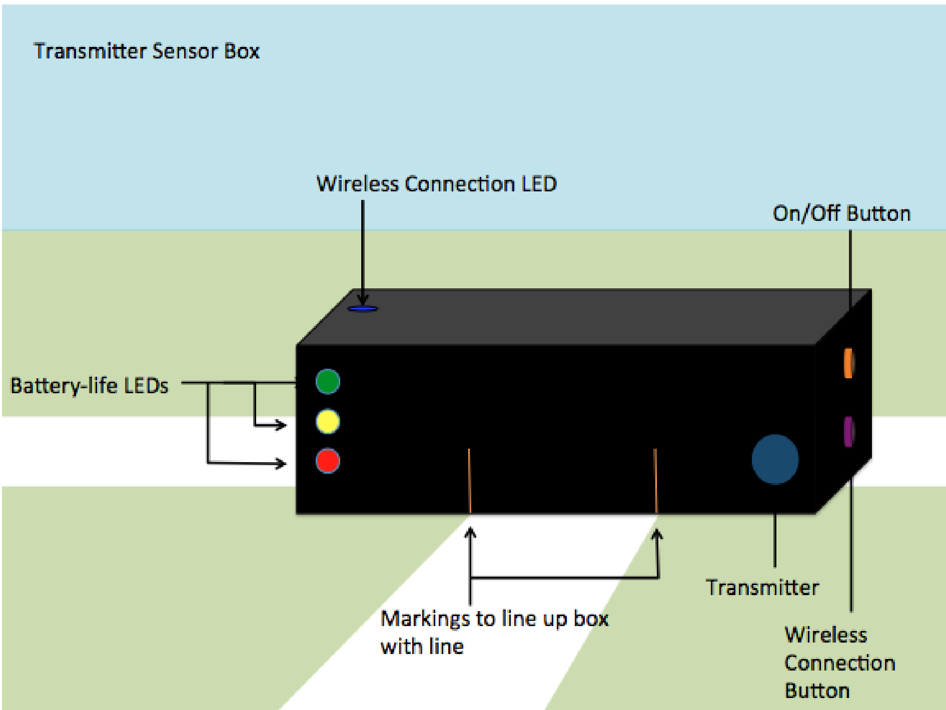

Figure 4: Emitter Physical Design

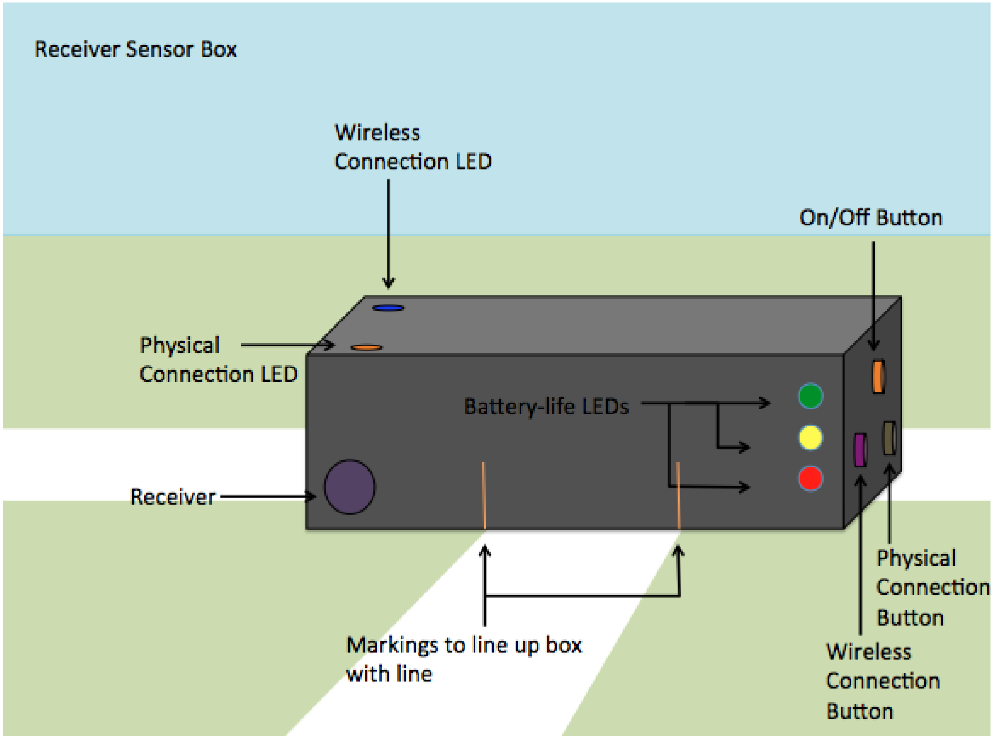

Figure 5: Receiver Physical Design

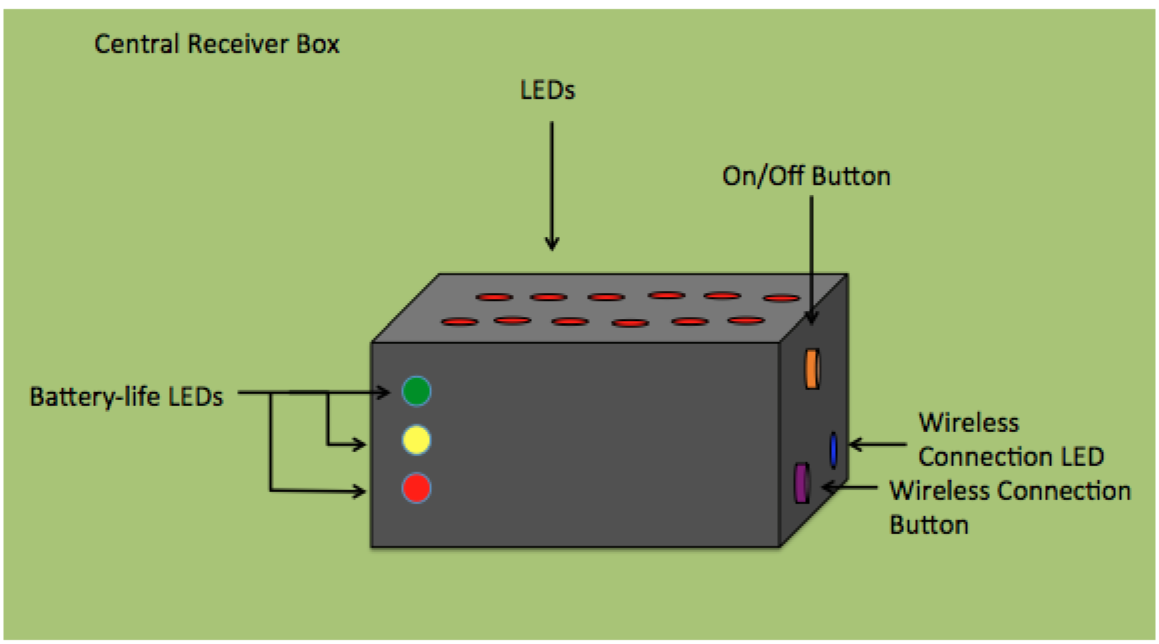

Figure 6: Central Receiver Physical Design

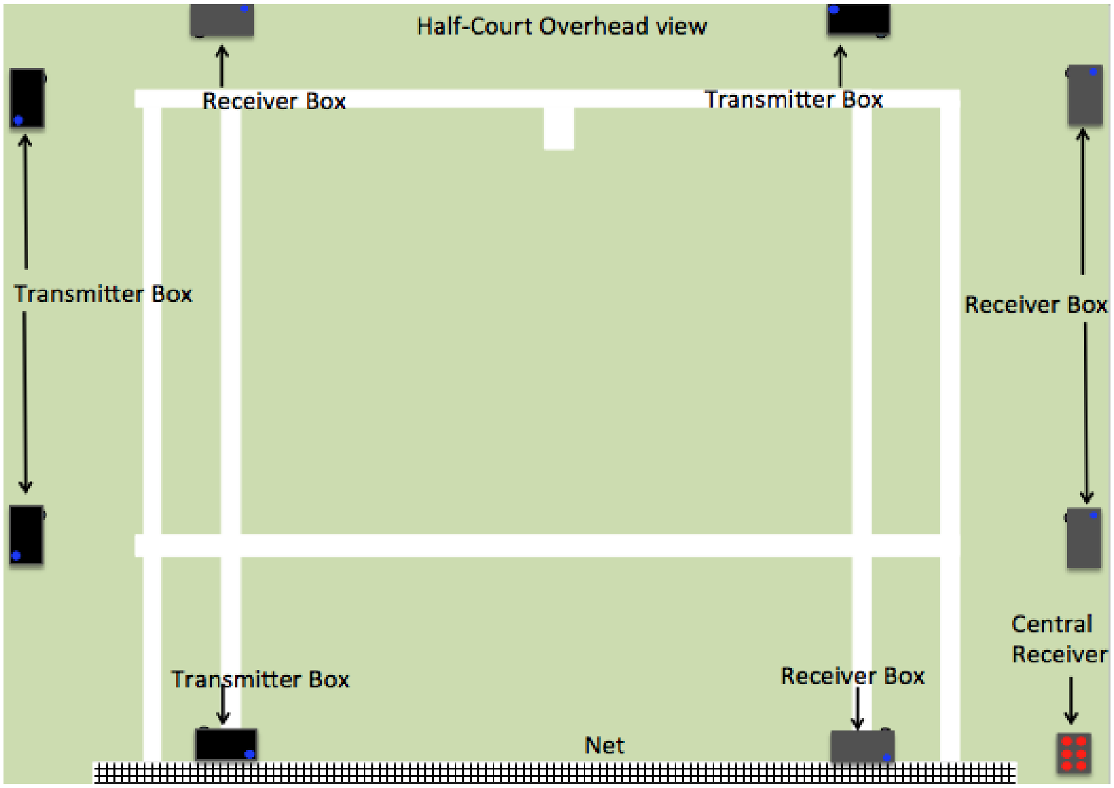

Figure 7: Half Court Diagram with Detailed Sensor Placement

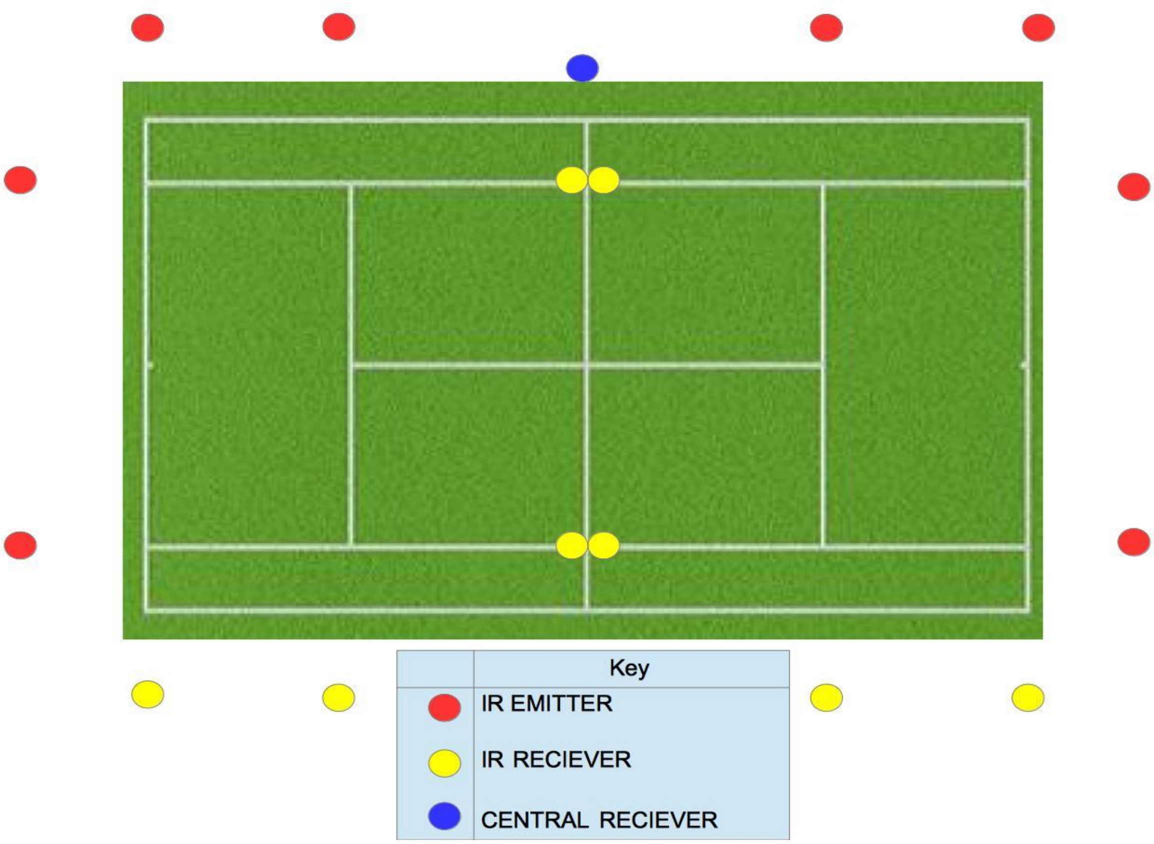

Figure 8: Tennis Court Full Diagram with Sensor Placement

2.1 Power Module

The power unit is essential for the three components of our project: the emitter, receiver, and the central receiver. The battery chosen is a 12V rechargeable Ni-Cd battery that will be used with a 12V to 5V DC-DC converter, and a 12V to 3V DC-DC converter to power the microcontroller and the wireless transceiver components respectively. The battery will also power the IR Emitter and the IR Receiver directly and the Battery Level LEDs, Wireless Status LEDs, Connection LEDs, and Display LEDs are powered through the microcontroller.

2.1.1 Battery Charging Circuit

This component will charge the 12V Ni-Cd Battery to its full capacity. The battery charging circuit has current regulator that will regulate the current at 4 A. The battery charging circuit will also make sure the battery is charged to 12 V.

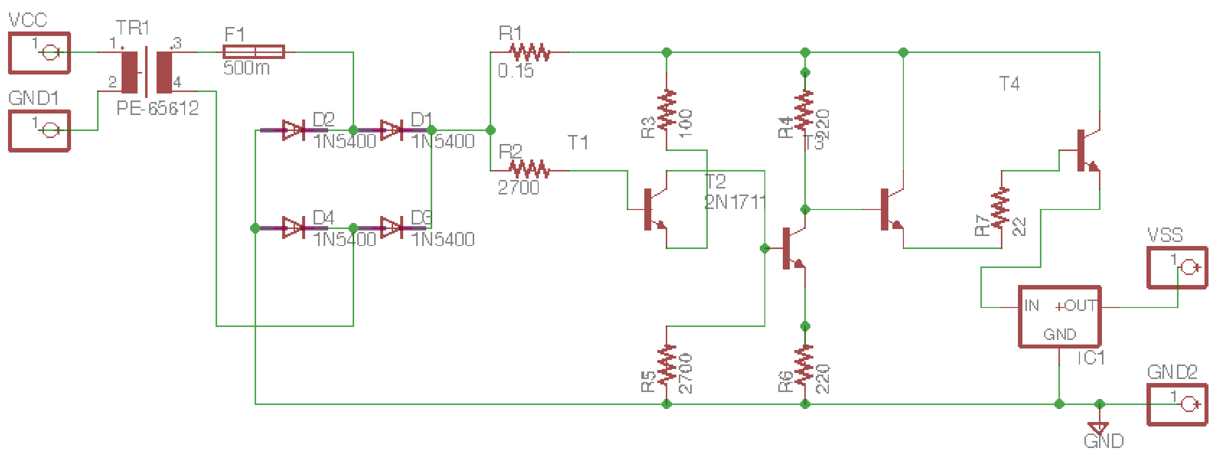

Figure 9: Battery Charging Circuit

2.1.2 12/5 V DC-DC Converter

This block drops down the battery voltage to 5 V in order to power the microcontroller and op-amps. The converter as seen in Figure 10, is a simple buck converter with a voltage regulator to stabilize the DC voltage.

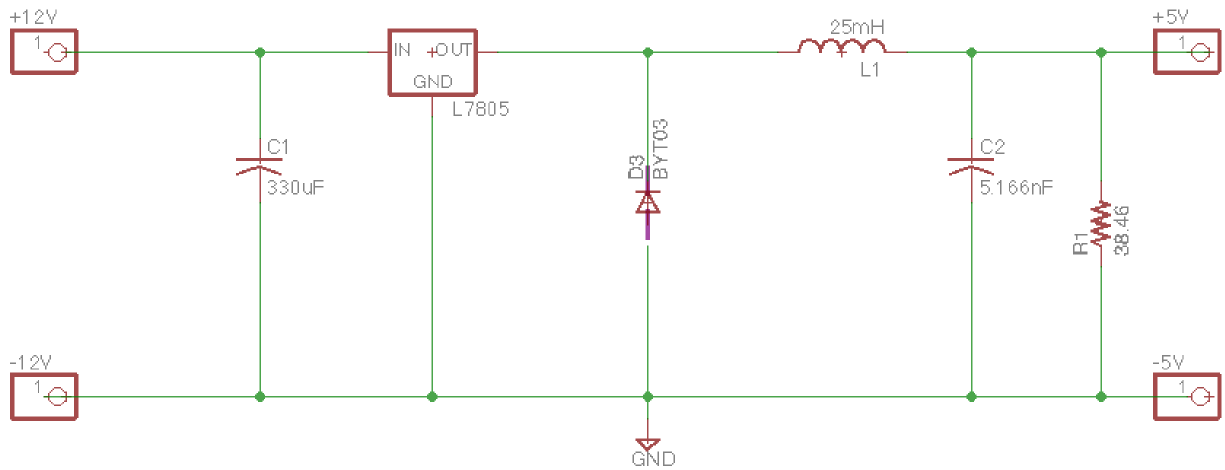

Figure 10: 12/5 V DC-DC Converter

2.1.3 12/3 V DC-DC Converter

This component converts the battery voltage to 3 V in order to power up the transceiver. The converter as seen in Figure 11, is a simple buck converter with a voltage regulator to stabilize the DC voltage.

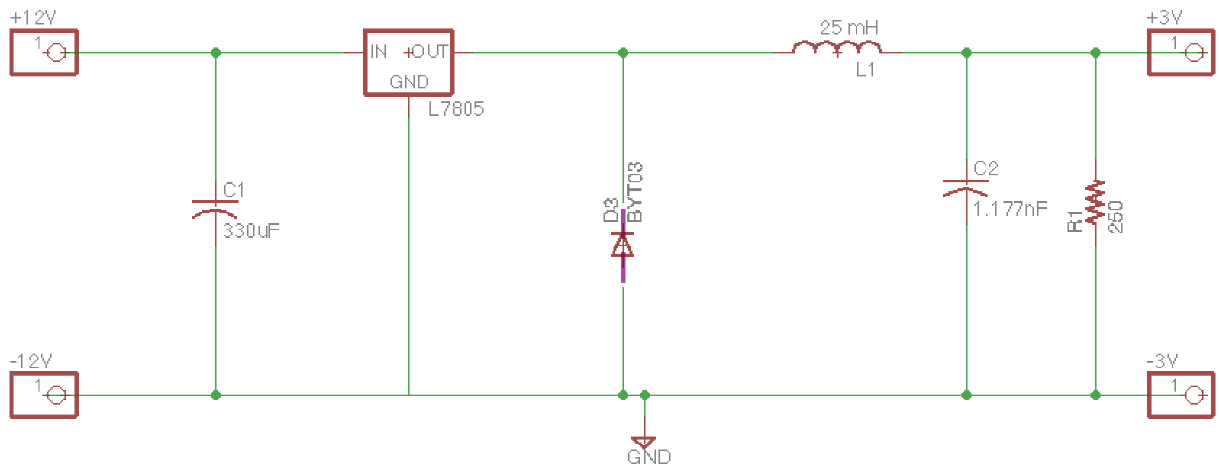

Figure 11: 12/3 V DC-DC Converter

2.1.4 Voltage Regulator

This component will be in the three blocks above. It'll be used to stabilize DC voltage in order to accurately output the necessary output voltage with minimal fluctuation.

2.2 Detection Module

The Detection Module is responsible for the IR Emitter, IR Receiver, hit detection circuit, and the ball/leg detection circuit. The sensors will send an analog signal to the hit detection circuit to determine if the ball was hit or not. If the ball was hit, the ball leg detection circuit will determine whether or not the hit was due to a ball or outside source (such as a foot).

2.2.1 IR Emitter

This component is a photoelectric sensor that will transmit a beam of infrared light to the IR receiver unless the beam is broken by an object. It operates between 10 - 30 V. The power the emitter will consume is 1.56 W.

2.2.2 IR Receiver

This component will receive an infrared beam sent from the IR emitter and will transmit current only if the beam is not broken. It operates between 10 - 30 V. The power the receiver will consume is 1.56 W.

2.2.3 Hit Detection Circuit

This component will take the data from the sensors, determine whether or not the beam has been broken and pass the data to the ball/leg detection. It consists of a transimpedance amplifier (TIA), to convert the receiver output current into voltage, and an inverter. When no current is flowing from the receiver, a high signal will be passed to the ball/leg detection circuitry. When high current is flowing from the receiver, a low signal will be sent to the ball/leg module.

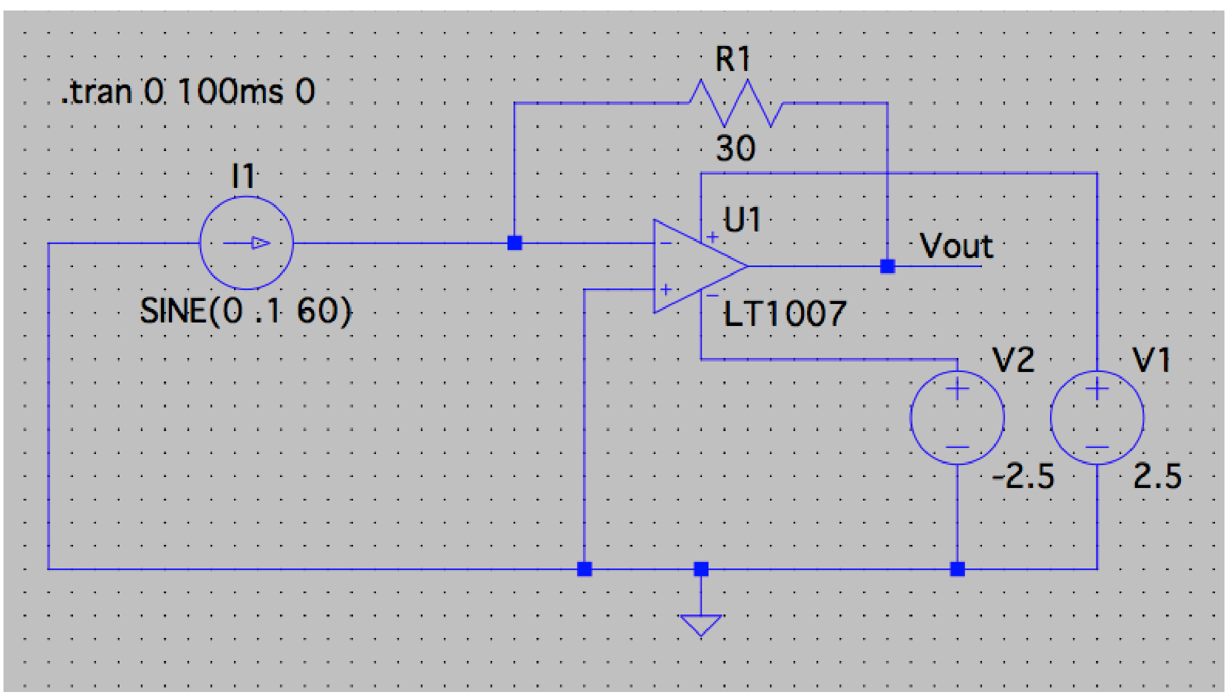

Figure 12: Transimpedance Amplifier Circuit

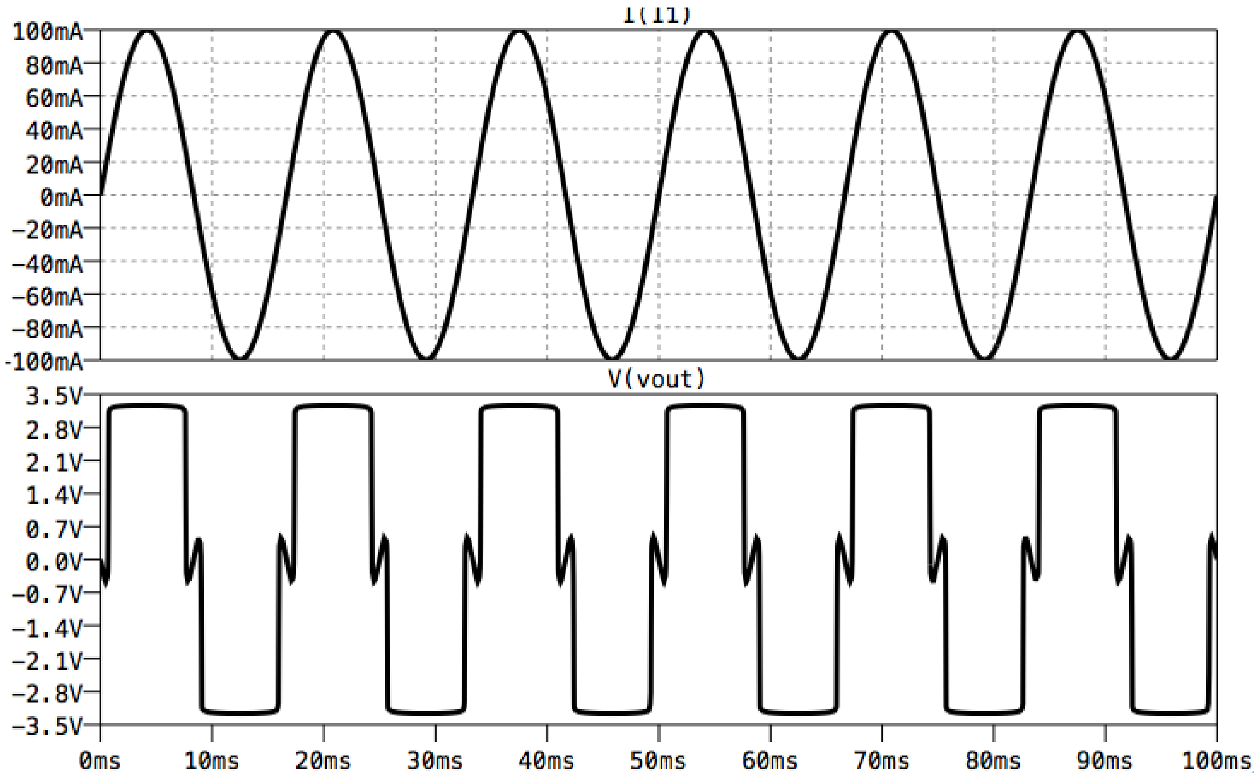

Figure 13: Transimpedance Amplifier Simulation

2.2.4 Ball Leg Detection

This component will attempt to determine whether or not a tennis ball caused the boundary hit. We will be using an analog integrator circuit to integrate over the duration of the beam break. If the voltage is too high (the beam has been broken for too long), the microcontroller will pass a low voltage to the display LEDs. If not, an output high will be sent. The slowest time found (in calculations below) that a tennis ball will take bounce across the IR beam is 0.0121 seconds. The fastest a human foot could break the beam was calculated to be .017 seconds, using the world record values for fastest sprinter & average shoe size. In case of small ball error, we use the latter value as our maximum output voltage for a boundary hit.

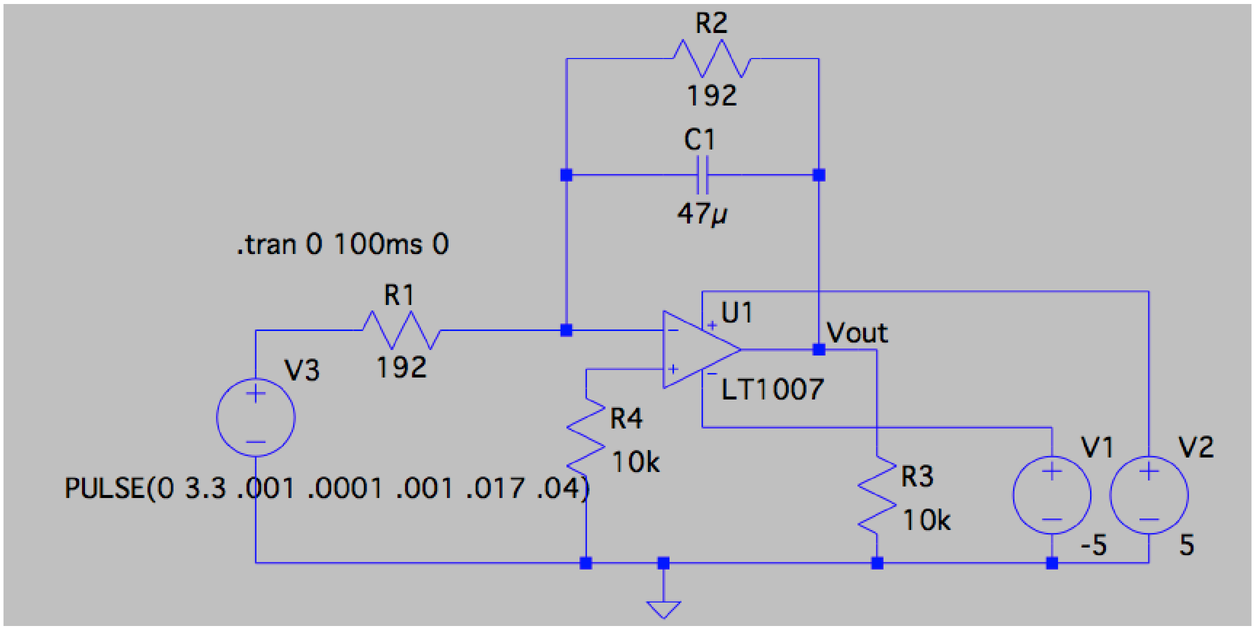

Figure 14: Ball/Leg Detection Analog Integrator Circuit

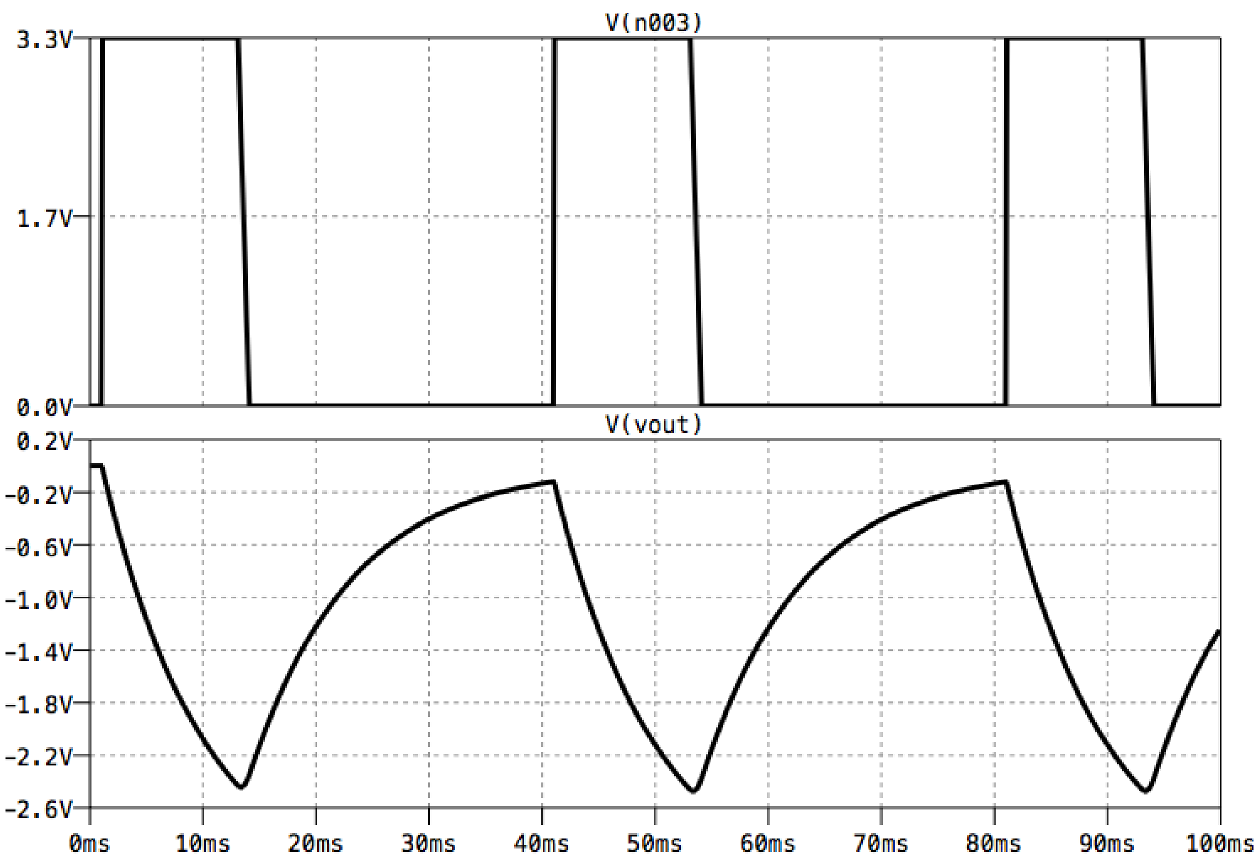

Figure 15: Ball/Leg Detection Analog Integrator Maximum “Ball Hit” Simulation (Ton = .012s Vmax = 2.5V)

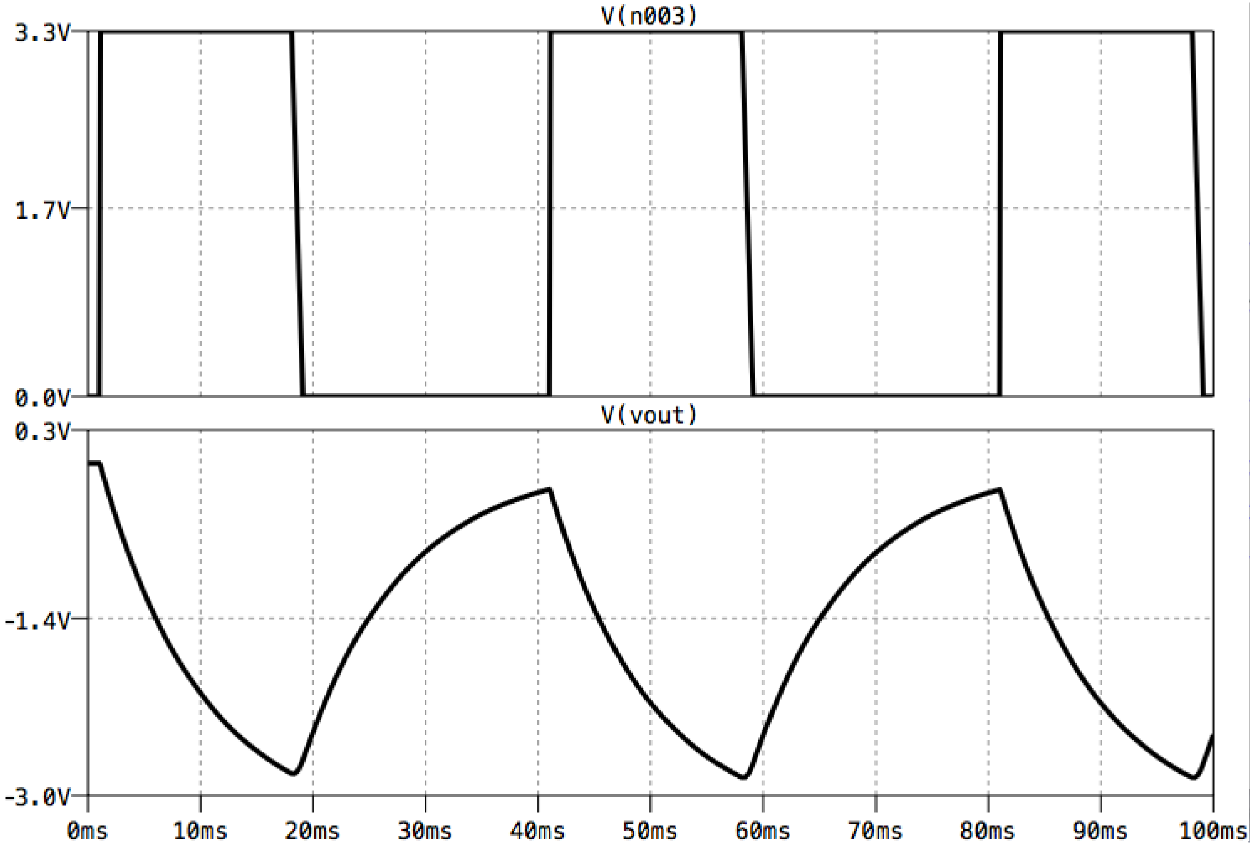

Figure 16: Ball/Leg Detection Analog Integrator Minimum “Leg Hit”Simulation (Ton = .017s Vmax = 2.8V)

2.3 Display Module

The display module is essential for showing the user the battery life, whether the emitter and receiver are connected, whether the transmitter from the receiver’s device and the receiver in the central receiver device are connected, and the outcome of a ball breaking the line.

2.3.1 Battery Level Indication

This component will notify the user of the battery level of the sensors to indicate when the sensors must be charged. It will consist of three different LEDs (green, yellow, and red) per receiver and emitter. The turn on voltage for the LEDs is in the range 1.8 V to 3.3 V.

2.3.2 Wireless Indication

This component will notify the user when the individual receivers are paired with the central receiver as well as notify the user if the network is set up. It will consist of a blue LED on each receiver as well as a blue LED on the central receiver. The blue LED on the receivers will notify the user if each is paired with the central receiver. It will light up if connected to the network, blink if attempting to connect, and turn off if unconnected. The blue LED on the central receiver will be on if the network is set up and available to be paired with. The network will be set up by the wireless chip, ZigBee, on the central receiver using the receiver mode. The receivers will pair to the central receiver using the transmit mode on the ZigBee in the receiver. The ZigBee and microcontroller on each device will send the corresponding high or low signal to the LEDs. The turn on voltage for the LEDs is in the range 1.8V to 3.3V.

2.3.3 Detection Indication

This component will tell the user if the ball is in or out. It consists of approximately 50 red LEDs located on the central receiver that will light up if the microcontroller transmits a boundary hit signal.

2.3.4 Physical Connection Indication

This component is used to check whether or not the emitter and receiver blocks are aligned correctly, so that the IR beam from the emitter is detected by the receiver when nothing is blocking the beam. It consists of a button and an orange LED on each receiver block. When the button is pressed, the microcontroller will check if the appropriate voltage is seen by the hit detection block, and turn on the LED if the appropriate voltage is seen. The microcontroller will be using the hit detection circuitry as the voltage input. It will output low voltage to the LED if the hit detection circuit reads high (beam broken) and high voltage to the LED if the hit detection circuit reads low (beam unbroken).

2.3.5 Microcontroller

This component is used to monitor the battery level for the Ni-Cd battery on the emitter, receiver, and central receiver. It is also used to send and receive the wireless signal from each receiver to the central receiver. The microcontroller used is an ATmega328P has a frequency of 10 MHz which is fast enough for our requirement of 0.01 seconds for the slowest speed of the tennis ball. The operating voltage is between 1.8 - 5.5 V.

2.3.6 Wireless Chip

This component will be used to receive the wireless signal from the eight receivers and send a signal to the LEDs to turn on if the beam was broken. The receiver used will be a TRM-315-LT which has a range of over 115 feet. The frequency used will be in the 900MHz range. There will be eight channels being used and for applications where it is on multiple courts, there are up to 100 channels on the receiver/transmitter. The receiver can accept both analog and digital inputs which can be used for debugging purposes.

2.4 Requirements and Verifications

Block	Requirement	Verification	Points
Battery Charging Circuit	The battery charging circuit will stop charging the circuit if the temperature of the battery is over 45 degrees Celsius.	Use an infrared thermometer to check the temperature of the Ni-Cd battery	4

	The circuit will stop charging the battery when it is at 12 V $\pm$ 2% .	Use an Digital Multimeter to check the value of the battery while the battery charging circuit is charging the battery	
12/5 V DC-DC Converter	Accept an input of 2-12 V and deliver a steady output of 5 V.	Vary the input voltage by 0.1 V between 2 V and 12 V with a DC power supply while measuring the output voltage with multimeter.	2
12/3 V DC-DC Converter	Accept an input of 2-12 V and deliver a steady output of 3 V.	Vary the input voltage by 0.1 V between 2 V and 12 V with a DC power supply while measuring the output voltage with multimeter.	2
Hit Detection Circuit	Must be able to detect a boundary hit given different current magnitudes flowing from the receiver. It must recognize 0-75mA $\pm$ 5mA as a boundary hit and 75mA-130mA $\pm$ 5mA as a cleared hit.	Use a waveform generator to input different current magnitudes into the hit detection module: 0mA, 20mA, 40mA, 60mA, 80mA, 100mA, 120mA, and 130mA. Use an oscilloscope to measure the output voltage and check for the accurate response (output high for boundary hit & output low for cleared hit).	5
Ball/Leg Detection	Must recognize a “ball hit” as a beam break less than .012s $\pm$ 2.5% and a “leg hit” as a beam break greater than .012s $\pm$ 2.5%. Circuit must reset (output voltage returns to zero) after .012s $\pm$ 5%.	Use a waveform generator to input a square wave with different T_{on} durations into the ball leg detection module: .0025s, .005s, .0075s, .01s, .0125s, .015s, .0175s, .02s, .0225s, and .025s. Use an oscilloscope to measure the output voltage sent to the Display LEDs and check for the accurate response (output high for “ball hit” & output low for “leg hit”). For each test above, using an oscilloscope, measure the time it takes for the output of the analog integrator voltage to return to zero.	15
Battery Level Indication	Battery level lights must turn on and off according to the battery voltage. The green LED must turn on if the voltage is 12V $\pm$ 3.7%, the yellow LED must turn on if the voltage is 11.475 V $\pm$ 2% and	Use a digital multimeter to check that the correct LED is lit when a certain voltage is applied to the logic.	2

	the red LED must turn on if the voltage is less than 11.025 V $\pm$2%.		
Wireless Indication	Central receiver must create wireless network available to all receivers within 70 ft. Multiple receivers must be able to pair with that network and detect connection loss. LEDs must light up corresponding to correct wireless connection.	Test that the receiver accepts and processes a signals from the transmitter from a distance of 70 feet away. Test that the receiver can accept a range of frequencies from the transmitter based on the data from the microcontroller Test that the LED shuts off when the connection is interrupted by the transmitter to the receiver Test three different types of signals: constant connection, pairing connection, and no connection and verify that the LED status is correct	15
Detection Indication	The display LEDs must light up within 5s of a detected boundary hit. The display LEDs must remain on for 5s +- 1s so that the players have time to process the boundary ruling. Each display LED must emit 5 lumens $\pm$ 5% so it can be seen at a distance of 50 ft (the furthest you are from the net of the tennis court while playing).	Use an oscilloscope to measure the duration between when the boundary hit signal is transmitted from the microcontroller and when the LEDs light up. Use an oscilloscope to measure the duration the LEDs are on after initially lighting up. Use an oscilloscope to read the voltage and current to calculate power. From there, use the watts to lumens formula and the luminous efficacy of 62 lm/W to ensure that the brightness is sufficient.	3
Physical Connection Indication	LED must light up if the IR beam is connected between emitter and receiver. It must recognize current through the receiver between 75mA-130mA $\pm$ 5mA as a connected beam and 0-75mA $\pm$ 5mA as an unconnected beam.	Use a waveform generator to input different current magnitudes into the hit detection module: 0mA, 20mA, 40mA, 60mA, 80mA, 100mA, 120mA, and 130mA. Use an oscilloscope to measure the output voltage and check for the accurate response (output high for connected	2

		beam & output low for unconnected beam).	

2.5 Risk Analysis

Our most important challenge that we choose to elaborate on is having the sensor differentiate between a ball and a person's foot. Even though the sensors we are building will be outputting a light if a ball is detected out, it is distracting to have the sensors light up unnecessarily and it can also cause confusion on the court. In order to overcome this challenge, we will be building our sensors to also determine how long the beam is broken. A bouncing ball and a human's foot will move at different speeds.

Using the data from "Follow The Bouncing Ball - Ball/Court Interaction" [4], the slowest the ball travels before bouncing is 28 mph and it travels 16 mph after bouncing. Using the same data, we found the angles of the ball to be 25 degrees and 42 degrees respectively. We choose these numbers because in tennis, the slowest shot is the underspin.

Using these speeds and the angle of impact we can calculate how long the ball would break the beam for.

$$y = V_y * \sin(\theta) \qquad (1)$$

$$28\,mph = 12.21\,\frac{m}{s}$$

$$16\,mph = 7.51\,m/s$$

$$t_{before} = \frac{3\,cm}{5.19\frac{m}{s}} = 0.0058\,s \qquad (2)$$

$$t_{after} = \frac{3\,cm}{7.15\frac{m}{s}} = 0.0063\,s \qquad (3)$$

$$t_{total} = t_{before} + t_{after} = 0.0121\,s \qquad (4)$$

In order to be safe, we will round the time a ball breaks the beam to 0.015 seconds to account for any extraneous shots.

A human's foot will break the beam for longer because a tennis shoe because the cross-sectional area of a tennis ball is about 5.73 in^2 while the cross-sectional area of a shoe is on average about 22.5 in^2. The foot is also placed there and stays in place for longer while a tennis ball will bounce. We tested this theory by recording a ball bouncing at the same time a person is running. With somewhat good accuracy, we were able to place our feet next to where the ball bounced. By slowing down the video, we were able to see that our feet would break a beam for longer than a ball.

Anyone who has watched professional tennis has most likely seen a line challenge. When a player challenges a line call, the umpire looks at the Hawk-Eye reading to see if the ball is in or out. The Hawk-Eye reading is also made public for everyone to see. Figure 4 is an image of a Hawk-Eye reading. As you can see, the ball skids when it bounces. This skid can create a challenge for our sensors. If the sensors are placed right on the edge of the line, then it may incorrectly call balls that hit the line but skid out as out when technically the ball is in. To overcome this challenge, the sensors will be placed a length of 1.35 inches away from the line (the radius of a tennis ball). This will allow the sensors to only blink when the ball is fully out.

The final challenge is making sure the sensors are waterproof and won't be affected if they get hit or stepped on. In order to waterproof the sensors, we will be enclosing them hard plastic shell similar to a Go-Pro. Ideally, a tennis player would be able to use good footwork to avoid running into the sensors, but to account for inexperienced players, we will make a shell for the sensors that will prevent them from being damaged when stepped on. This shell will also protect the sensors if they are hit by a racquet. Another solution that we will work towards is building strong enough sensors that can be put at the end of the court where no players will trip over it.

Figure 15: Hawk-eye Reading [2]

3. Ethics and Safety

This device will be used for recreational tennis and maybe even for high school tournaments. There are some safety requirements that need to be followed when using this device. Even though the device is water resistant, it is not meant to be use when it is raining. This device is susceptible to heat. When it is very hot outside, the court will be very hot as well. Therefore, in order to protect the sensors, place a non-conductive material under the device. This will prevent overheating. It is important to make sure the sensors are facing each other when the system is on. Do not point the laser diode sensors at anything else besides the photodiode sensor, especially another human, when the system is on. Also, be aware of where the sensor is on the court. Even though it is protected from most forms of damage, it does not protect the user from injuring themselves from tripping over the device.

It is important that we abide by the IEEE Code of Ethics [3]. We will be making decisions on our design with the safety of the user in mind. We aim to pull back the sensors as far as possible, while still receiving accurate results, to prevent players from tripping and injuring themselves. We will be providing directions on how to place sensors on the court and how to properly charge the battery for the sensor. We will be accepting criticisms and suggestions on our design especially the wireless connections portion. None of us have experience setting a wireless network so we will be asking for help from professors as well as reading up on documentation. Lastly, our sensors will ethically call a ball out within a small range of error. It is important that the sensors are accurate as the goal of the project is to take away any dishonesty in the sport.

4. Cost and Schedule

4.1 Cost Analysis

4.1.1 Labor

Name	Hourly Rate	Hours	Total	Total x 2.5
Neil Bhide	$30.00	300	$9,000.00	$22,500.00
Andreya Dart	$30.00	300	$9,000.00	$22,500.00
Modhura Kar	$30.00	300	$9,000.00	$22,500.00
Total				$67,500.00

Table 1: Labor Costs

4.1.2 Parts

Description	Quantity	Manufacturer	Vendor	Cost/Unit	Total Cost
TRM-900-NT	9	Linx Technologies	Digi-Key	$28.31	$254.79
MLSI - MINI-EYE Standard LED, Thru-Beam, Infrared, Cabled	8	Tri-Tronics	Tri-Tronics	$24.00	$192.00
MLRC-18 - MINI-EYE 18 mm Receiver, Laser Thru-Beam, NPN, Connector	8	Tri-Tronics	Tri-Tronics	$61.00	$488.00
NiCd Battery Pack: 12V 400 mAh (4.8Wh, 10x2/3AA)	9	Custom Battery Packs	Batteryspace	$17.00	$153.00
ATmega328P	9	Atmel	Microchip	$1.94	$17.46
Total					$1,105.25

Table 2: Component Costs

4.1.3 Grand Total

Section	Total
Labor	$67,500.00

Parts	1,105.25
Grand Total	$68,605.25

Table 3: Grant Total Cost

4.2 Schedule

Week	**Task**	**Responsibility**
02/20/17	**Mock Design Review (Wed)**	All
	Research and Select Sensors	Neil
	Research and Select Hardware components	Andreya
	Prepare Design Review	Modhura
02/27/17	**Design Review (Wed)**	All
	Purchase hardware & all parts, research on wireless communication	Neil
	Collect battery charging battery circuit specifications	Modhura
	Design Analog Integrator and Transimpedance Amplifier	Andreya
03/06/17	**Soldering Assignment Due (Fri)**	All
	Study wireless connectivity and order parts	Neil
	Hardwire battery charger and work on wireless connectivity	Modhura
	Hardwire and test analog integrator and transimpedance amp	Andreya
03/13/17	Work on wireless connectivity and central receiver	Neil
	Create PCB layout for battery charger and assist Neil.	Modhura
	Create PCB layout of analog integrator and transimp. amp and assist Neil	Andreya
03/20/17	**Spring Break/Catch up with any work**	All
03/27/17	**Program microcontroller**	All
	Prototype sensor boxes and output module	Neil
	Test battery and battery charger efficiency	Modhura
	Implement analog integrator and transimp. amp with sensors	Andreya
04/03/17	Implement microcontroller with central receiver and debug	Neil
	Test and debug sensors module power module	Modhura
	Work with Neil to connect sensors module to output module	Andreya
04/10/17	**Test and Debug Entire System**	All
04/17/17	**Prepare for Mock Demo and write Final Paper**	All
04/24/17	**Prepare for Demonstration and Presentation**	All
05/01/17	**Prepare Final Paper and Checkout of Lab**	All

5. References

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