Portable Sport Boundary Sensors
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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 lights.

The sensor arrangement will be through-beam with a laser diode as an emitter and a photodiode as the receiver. The sensor 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

- Length of Use: The system must be able to run for a minimum of three hours when the battery is fully charged
- Portability: The sensors must weigh less than 2 pounds so it can be transported between courts
- Accuracy: The sensors must be able to detect 90% of the ball correctly

2. Design

The portable sport boundary sensors will have three main modules to meet the requirements: a power supply, a sensor block, and a display block. The power supply allows the system to be powered throughout its use through rechargeable a Ni-Cd Battery. We will be designing an AC/DC converter as well as a DC/DC converter to invert the power and then step down the voltage to be used for our sensor design. Our detection block consists of our photoelectric sensor design and microcontroller. These components process the sensor data and generate an output. The output block consists of two sets of LEDs, one for showing the battery life and one for showing if the ball is in or out.

![Figure 1: High Level Block Diagram](image-url)
Figure 2: Emitter Block Diagram

Figure 2: Receiver Block Diagram
Figure 3: Central Receiver Block Diagram

Figure 4: Tennis court diagram with sensor placement
2.1 Power Module

The power module will be used to power the device and the sensors through a rechargeable Ni-Cd battery. The battery will output 12 V.

2.1.1 Battery Charging Circuit

This component will charge the Ni-Cd Battery to its full capacity.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>The battery charging circuit will stop charging the circuit if the temperature of the battery is over 45 degrees Celsius</td>
<td>Use an infrared thermometer to check the temperature of the Ni-Cd battery.</td>
</tr>
</tbody>
</table>

2.1.2 Ni-Cd Battery

This component will provide the power for the portable boundary sensors

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>The sensors must be able to detect if a ball is in or out for a minimum of 3 hours. Being able to detect is flashing a light at the central receiver if the ball is within one radius of a tennis ball outside of the line</td>
<td>Use the sensors for 3 hours total (1 hour; three distinct time). Repeat every 2-4 days.</td>
</tr>
</tbody>
</table>

2.1.3 Voltage Regulator

This component is used so that the Ni-Cd Battery does not get destroyed if the voltage falls below a certain threshold value. Instead, it should shut the battery down.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>The battery should shut off if it falls below 2.75V.</td>
<td>Use an oscilloscope and power supply to determine if the voltage regulator will shut off when the voltage falls below 0.7 V</td>
</tr>
</tbody>
</table>

2.2 Sensor Module

This module will be the brains of our project. It will receive signals from the sensors and then decide whether the ball is in or out and notify the user with outputting a light.

2.2.1 IR Emitter

This component is a photoelectric sensor that will transmit a beam of infrared light to the IR receiver using a light emitting diode unless the beam is broken.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must be able to reach the IR receiver that is at least 39 feet away.</td>
<td>Test the maximum distance of 39 feet in both indoor tennis court lighting as well as sunny outdoor tennis court lighting.</td>
</tr>
</tbody>
</table>

### 2.2.2 IR Receiver

This component will get an infrared beam from the IR emitter and will transmit current only if the beam is not broken.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must be able to sense the infrared beam the IR emitter that is at least 39 feet away.</td>
<td>Test the maximum distance of 39 feet in both indoor tennis court lighting as well as sunny outdoor tennis court lighting.</td>
</tr>
</tbody>
</table>

### 2.2.3 Hit Detection

This component will determine if the beam has been broken or not. If the beam is broken, it will then determine if it is a ball or a leg. If the beam is not broken, it will reset and check if the beam is broken again.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must be able to detect if the beam is broken at least 80% of the time.</td>
<td>Check the output of the hit detection comparator for different types of tennis ball speeds ((20% lobs, 20% forehands, 20% backhands, 20% serves, 20% volleys) &amp; (50% Wilson balls, 50% Penn balls) and track success rate for 100 test case</td>
</tr>
</tbody>
</table>

### 2.2.4 Ball Leg Detection

This component will only be used if the beam is broken. It will check if the thing that broke the beam is a tennis ball or a leg. The slowest time found (in calculations below) that a tennis ball will take bounce at the line is 0.01 seconds, so if the beam is broken for longer, then no signal is sent to the display module. If the beam is broken for less than 0.01 seconds, a wireless signal is sent to the display module.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must be able to detect the difference between a ball and other objects at least 80% of the time.</td>
<td>Check the output of the ball leg comparator for leg detection at different speeds (25% standing there, 25% between 0 and 3 miles per hour, 25% between 3 and 6 miles per hour and 25% above 6 miles per hour)</td>
</tr>
</tbody>
</table>
Figure 5: Ball/Leg Detection Analog Integrator Circuit

Figure 6: Ball/Leg Detection Analog Integrator Simulation
2.3 Display Module

This module will be what the users see when using the sensor system. There is one central location for display the detection of the ball to allow for ease of user experience. There are also individual battery level LEDs on each receiver and emitter.

2.3.1 Battery Level LEDs

This component will notify the user when the sensors need to be charged. Likewise, it will notify the user when the sensors are fully charged. The turn on voltage for the LEDs is in the range 1.8 V to 3.3 V.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control panel light must be green if the voltage is 12.15 ± 3.7%, yellow if</td>
<td>Use an oscilloscope to check that the correct LED is lit when a certain</td>
</tr>
<tr>
<td>the voltage is 11.475 ±2% and red if it is 11.025 ±2%.</td>
<td>voltage is applied to the logic.</td>
</tr>
</tbody>
</table>

2.3.2 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.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>The sampling period must be less than 0.01 ±5% seconds</td>
<td>Use and oscilloscope to determine that the sampling frequency is 0.01 seconds</td>
</tr>
<tr>
<td></td>
<td>±5%</td>
</tr>
</tbody>
</table>

2.3.3 Display LEDs

This component will tell the user if the ball is in or out. The display LEDs are only on the central receiver and will light up if the beam of light is broken for less than 0.01 seconds.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displays must be 5 lumens ± 5% so it can be seen at a distance of 50 ft</td>
<td>Use an oscilloscope to determine the voltage and current to get the power.</td>
</tr>
<tr>
<td>(the furthest you are from the net of the tennis court while playing.)</td>
<td>From there, use the watts to lumens formula and the luminous efficacy of 62</td>
</tr>
<tr>
<td></td>
<td>lm/W to ensure there is enough light.</td>
</tr>
</tbody>
</table>

2.3.4 Central Receiver

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.
### Requirement | Verification
---|---
ZigBee can communicate with any receiver that is less than 50 ft away ± 5 ft. | Set up a space that is 45-55 feet away from the receiver and ensure that there is pairing between the two devices.

#### 2.4 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.

\[
y = V_y \sin(\theta) \\
28 \text{mph} = 12.21 \text{m/s} \\
16 \text{mph} = 7.51 \text{m/s} \\
12.21 \times \sin(25) = 5.16 \\
7.15 \times \sin(42) = 4.78 \\
t_{before} = \frac{3 \text{cm}}{5.16 \text{m/s}} = 0.0058 \text{sec} \\
t_{after} = \frac{3 \text{cm}}{7.15 \text{m/s}} = 0.0063 \text{sec} \\
t_{total} = t_{before} + t_{after} = 0.0058 + 0.0063 = 0.0121
\]

In order to be safe, we will round the time a ball breaks the beam to 0.02 seconds to account for any extraneous shots.

A human’s foot will break the beam for longer because a tennis shoe, at its smallest height (at the toe), is 4 cm height. 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.

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 waterproof, 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 the reflector 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 and won’t be damaged, 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 are pulling back the sensors 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. It is important that the sensors are accurate as the goal of the project is to take away any dishonesty in the sport.
4. References


