ECE 445 Spring 2023 - Design Document

Footballytics

Team 16

Akshay Bapat(aabapat2)

Vibhav Adivi (vadivi2)

Varun Venkatapathy (vcv2)

Professor: Victor Gruev

TA: Xiangyuan Zhang

February 23, 2023

Contents

1 Introduction

1.1 Problem and Solution

1.1.1 Problem

American football, also known as gridiron, is a team sport played by two teams of eleven players on a rectangular field with dimensions of 120 yds by 53 ⅓ yards. Both sides of the field have a goalpost. The team in possession of the oval-shaped football aims to advance the ball down the field by running or passing it while the defense's purpose is to prevent the offense from advancing. A sport comprising two teams of eleven players, one team attempts to either score touchdowns or field goals by either passing or running the football, an oval ball. The offense, or the team attempting to score the ball, has four downs to move ten yards from where they started. If they accomplish this goal, they get a new set of downs based on where they were stopped [1]. This is decided by the referees, specifically the line judge, and is done through sight. Because so much scoring is done by humans, the accuracy of some rulings has come into question during key matches. With the advent of the new FIFA world cup ball and NBA basketballs [2][3] sporting cutting-edge sensory equipment allowing coaches to track ball movement and analyze player performance, we believe that there should be a solution to the inaccuracy of football and the subjectivity surrounding it. In addition, balls can get deflated over the course of the game, so pressure in the ball needs to be monitored as well.

1.1.2 Solution

Footballytics is our proposed solution to combat the inaccuracy that athletes may face during gameplay. This will be accomplished via a four-part system: sensor data collection, ultra wideband positioning, data transmission, and actuation. The football will be equipped with geolocation, pressure, acceleration and gyroscope sensors which would allow us to track free-fall and impact during game play, as well as its precise location. The sensors included in our device will allow referees to measure the speed of throws, the location, and pressure of the ball in real-time. Sensors in the football will be able to provide this data while having the ability to publish it to a computer using Bluetooth. The final part is using a visual LED to indicate when the requirements have been met for either a new set of downs, or touchdown.

1.2 Visual Aid

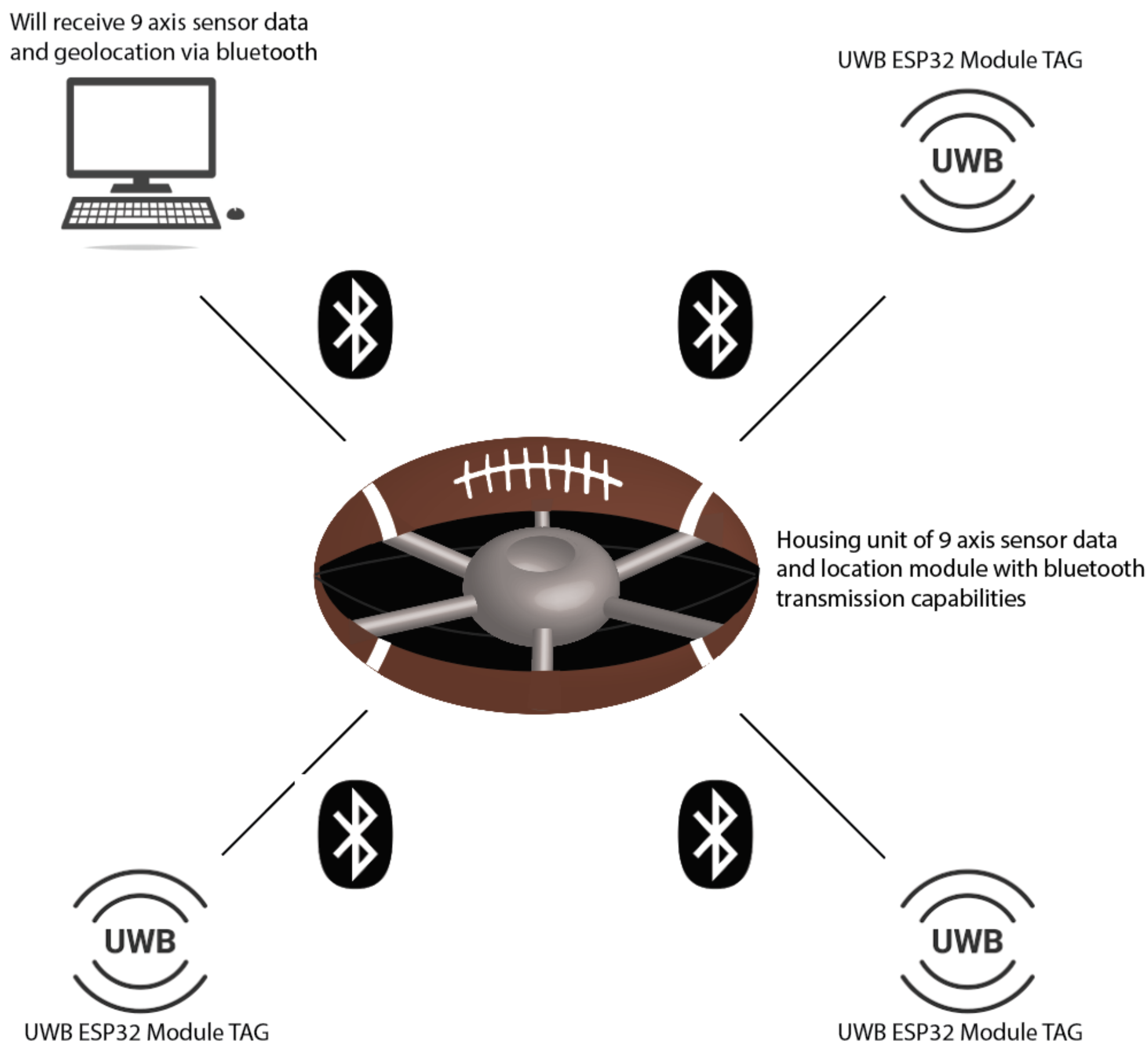

Fig. 1. Overview of the Footballytics Device operating in conjunction with UWB anchors for geolocation tracking.

1.3 High-Level Requirement List

The following list is the criteria we have determined to be necessary for success.

- Checkpoint 1: Tracking system capable of checking football positioning within a given space
  - The ESP32 Microcontroller acts as a continuous scanning radar that locks and communicates with a device, known as an anchor, to calculate its own location in respect to the anchor. The DW1000 is a fully integrated low power, single chip CMOS radio transceiver IC that allows the ESP32 to communicate with other anchors via Bluetooth.
  - Once the device is close to another UWB device it will calculate the time between devices and provide us with real time location and time tracking capabilities up to 10cm of accuracy.
  - Device will also be used to send the 9-axis sensor data to a device which can be used for viewing later.
- Checkpoint 2: 9-axis sensor data
  - The smart sensor BNO055 is a system that integrates a 14-bit accelerometer, a 16-bit gyroscope, a geomagnetic sensor, and a microcontroller that will allow us to track tangential acceleration, rotational acceleration and magnetic fields. The module will stay active during all parts of game-play. Axis data will be transmitted via bluetooth with speeds faster than 1ms.
- Checkpoint 3: Air-pressure sensor to track pressure of the space within the ball
  - Barometric sensor will be used to track pressure within the ball. NFL regulated footballs are typically between 12.5-13.5psi. Average “football sacks" can produce 1600 lbs of force on the ball [4]. The sensor will be able to withstand pressures up to 20 psi which will enable the sensor to provide accurate real-time readings.

2 Design

2.1 Physical Design

The overall physical design of the system will be encased in a 3D-printed spheroid. This spheroid will house the PCB systems we design. Attaching polyester fabric cord to each side of the ball panel we will keep the central housing unit anchored such that during game play the unit would not be damaged. The device is designed to be battery-operated for extra usability. We have implemented our charging capability in such a way that the modules will be functional while the device is charging.

2.2 Block Diagram

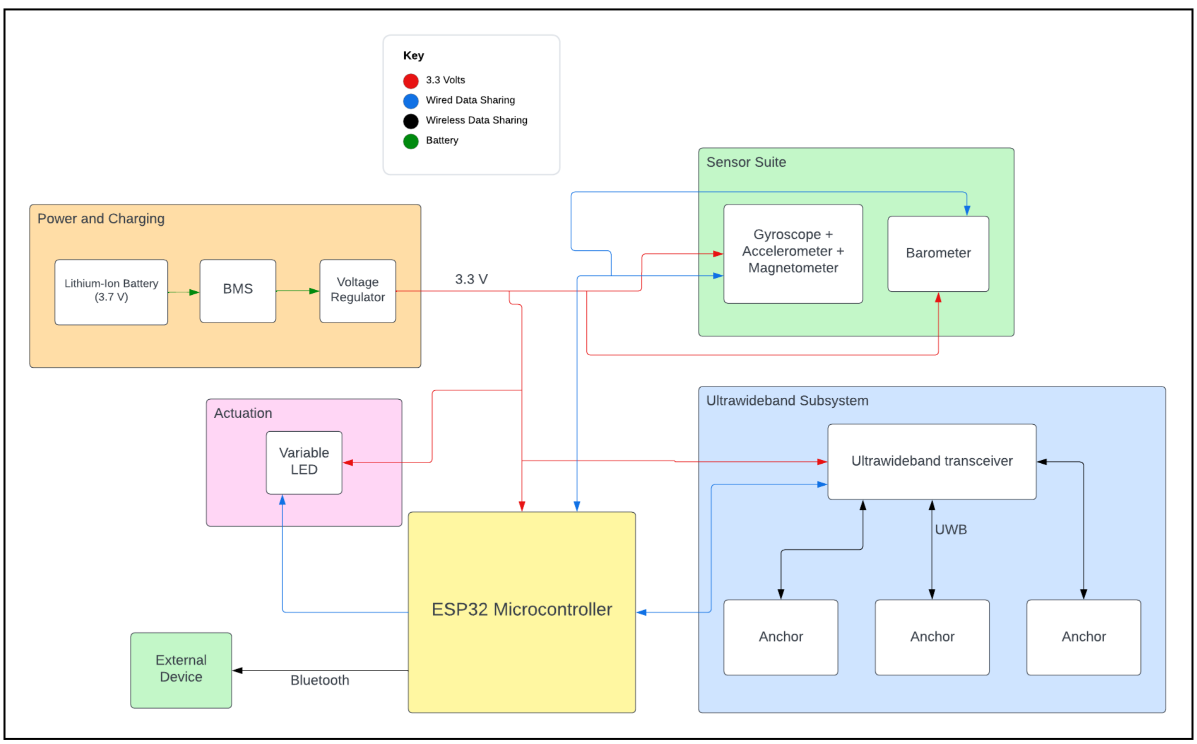

Fig. 2. Block diagram of system.

Figure 2 shows our block diagram with the four main subsystems: power and charging, sensors, actuation, and ultra-wideband. The microcontroller and the subsystems not including power and charging are supplied 3.3 volts from the power and charging subsystem. Most of the system seen above can be seen directly on the circuit board in the football, but the anchors in the Ultra-wideband subsystem are physically separate and communicate with the UWB module in the football. In addition, there is wireless data transmission via Bluetooth Low Energy between the ESP32 and an external computer in order to centralize the data during gameplay. Each subsystem is expanded upon below.

2.3 Subsystem Overview

2.3.1 Sensor Suite

This subsystem consists of a 9-axis motion sensor(accelerometer, gyroscope, magnetometer) and barometric sensor so that we can track metrics of different plays and throws while simultaneously always knowing where the ball is. The requirements for this subsystem include the accurate measurement and storage of tangential acceleration (via an accelerometer), rotational acceleration (via a gyroscope), and the strength of the local magnetic field (via a magnetometer) to determine orientation. This data will be sent to a local computer via bluetooth using the ESP32. The sensors will have an input of 3.3 volts. As recommended from the data sheet the input will have 2.1µF and 2 22µF capacitors. We intend to use the BNO055 device that will record all data measurements and will use the 10k Ω resistors to adjust the output of the module. The circuit includes MOSFET BSS138, and has resistors placed in series. For a visual reference refer to Figure 3.

Requirements	Verifications
● Output pins which relay the data being measured must have current passing through it.	● Probe the input of the BNO055 with voltmeter when batteries are connected to input and the Vout is maintained at constant 5 volts. After confirmation we use the ammeter to make sure that there is current coming from each of the OUTPUT pins.

Table 1: Requirements and Verifications for Sensor Suite

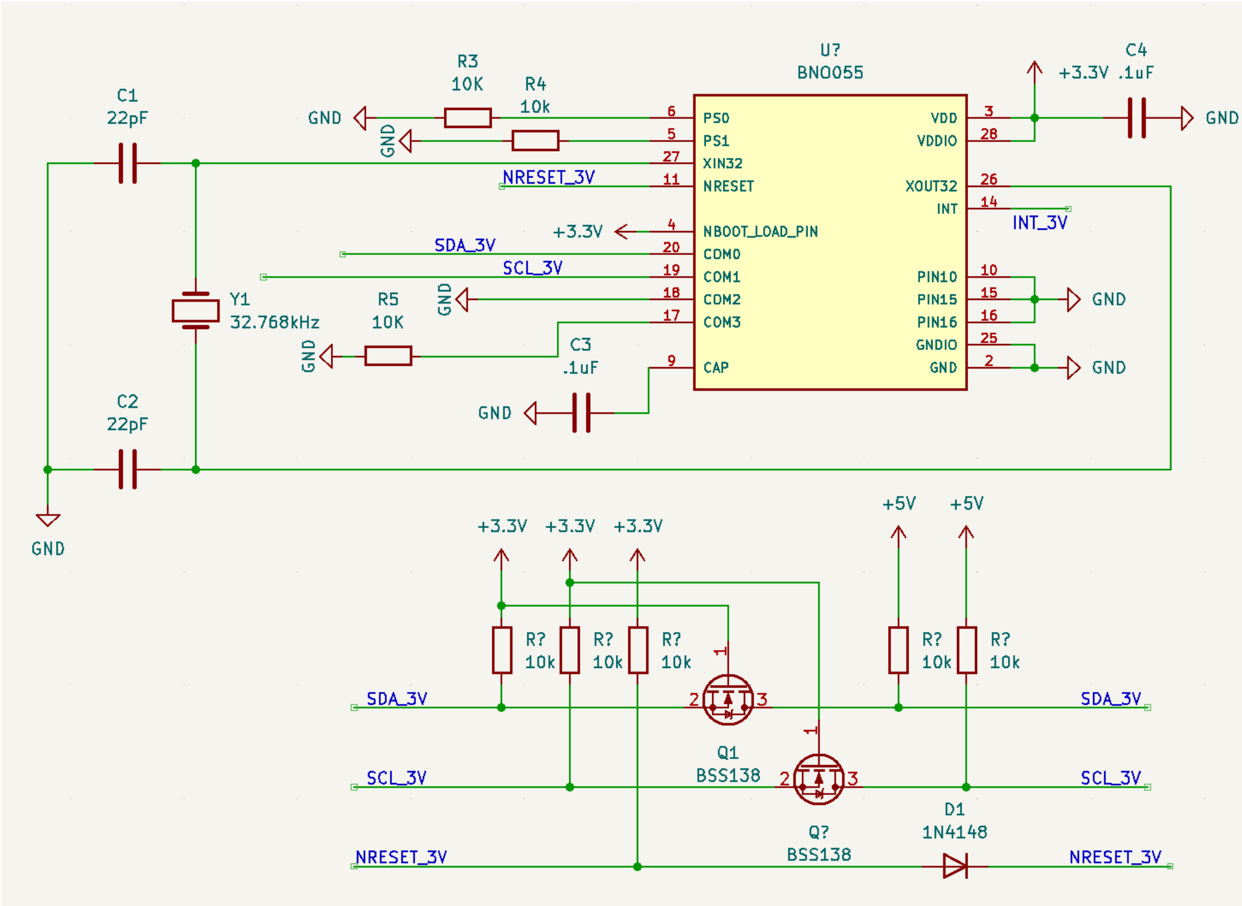

Fig. 3. Sensor Suite [5]

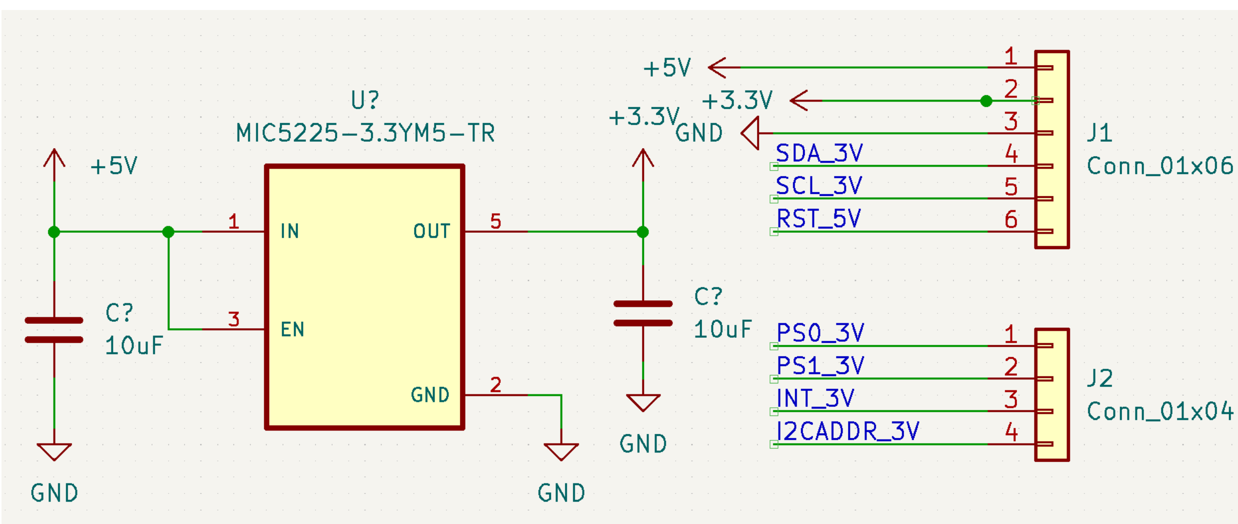

Fig. 4. Sensor Suite Connection to Module [5].

2.3.2 Power and Charging

This module will provide rated current for all the modules of our PCB at 3.3 volts. It will need to last the full length of a game, as well as overtime. Since the longest game in NFL history is 82 minutes, the requirement for this module will be to last at least four hours to accommodate any uncontrollable circumstances. Since our microcontroller, UWB module, and sensor module have current draws of 240 [6], 13.5 [7], and 12.3 [5] mA, respectively, a battery must be rated for at least 265.8 mAh with a capacity of four hours, as shown in section 2.4.

This module has three parts: a USB-C charging port, a charging circuit to allow our battery to recharge, and a 3.7V battery with a current output of 2000 mAH. We will use a Micro-USB port to actually provide voltage to our battery, as Micro-USB is very common and we will be able to charge from any computer. We will also need a circuit that recharges our battery, given some external voltage. We will use the MCP73831 chip in conjunction with an LED. The MCP73831 is a smart chip that can indicate when our battery is fully charged, such that a LED will light up when our battery has reached capacity.

Finally, we have a lithium-ion battery rated at 3.7 volts and 2000 mAH. From above, we know that our parts have a total current usage of 322.3 mAH. Most batteries are tested to last for four hours at .2 capacity [8], so in this case .2 of 2000 is 400 mAH. As well, since our parts are rated from 3.3-3.6V, we need to use two resistors in series to slightly bring down the voltage. We will use one 400-ohm resistor and one 3300-ohm resistor, and output the voltage from in between the two resistors.

Requirements	Verification
● Lithium-ion batteries must be able to last up to four hours.	● Set the battery using a programmable load to 3.7 V. Make sure the voltage does not drop below 3.3V, which is operating voltage. ● The battery is continuously outputting 400 mAH for four hours. We will test this by hooking a multimeter to the positive and negative leads and looking at the current output.
● Our battery can survive any football plays or conditions that are likely to occur	● We will protect the charging circuit in an enclosure. We will test it by simulating football conditions, such as kicking, throwing and catching.

Table 2: Requirements and Verification for Power and Charging

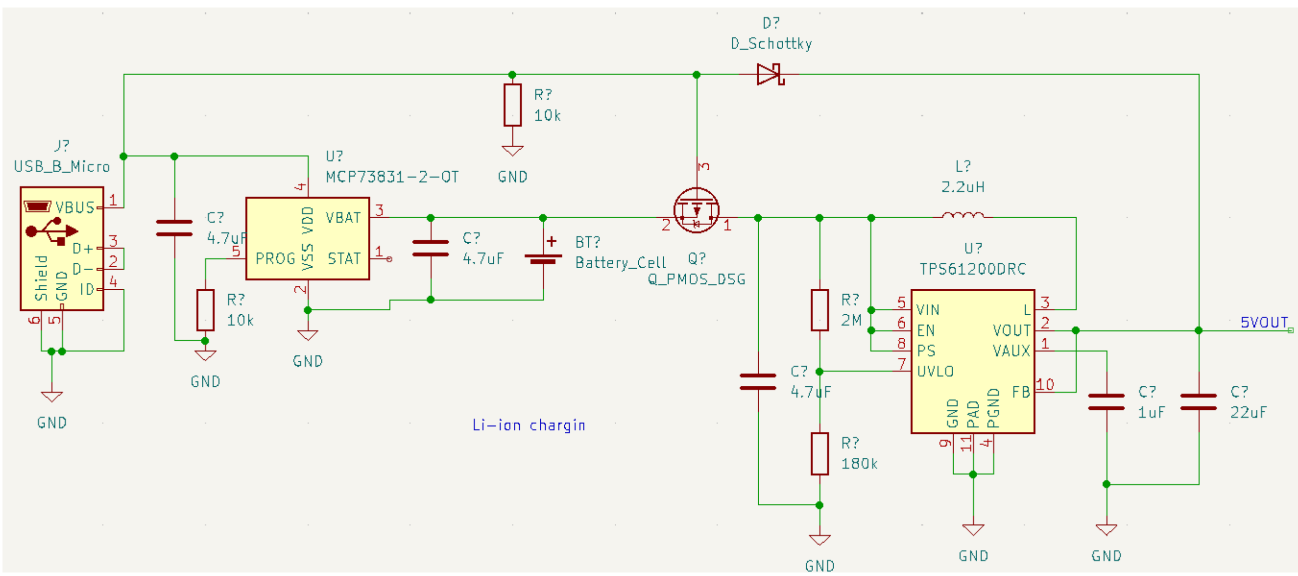

Fig. 5. Lithium-Ion Charging with Micro-Usb plug-in [9].

2.3.3 Ultra-Wideband System

The purpose of the Ultra-Wideband (UWB) subsystem is to accurately position the football in real-time. The UWB module we will be using is the DWM1000. The DWM1000 is a UWB module that contains a DW1000 UWB transceiver IC. The DW1000 is capable of accurately measuring the distance between two UWB devices within 10 centimeters by measuring the time it takes for a signal to travel between them [7]. Our system will be using a total of four DWM1000 modules. One of these modules will be on our main PCB in the football, serving as a "tag", while the other three will be around the perimeter of the playing field, serving as "anchors."

The UWB positioning system works by sending very short pulses of radio waves, which are transmitted at a high frequency. The frequency used by the DWM1000 is in the range of 3.5 to 6.5 GHz [7]. By using such a high frequency, UWB can achieve high-precision ranging and positioning measurements. The distance between two UWB devices can be calculated by measuring the time it takes for a radio wave to travel between them, and multiplying that time by the speed of light. The time measurement is very accurate, as it is typically measured in picoseconds (10^{-12} seconds) [10].

By using three anchors with known positions, we can use a process called trilateration to determine the position of the football. Trilateration is a method that uses three known points to find the location of a fourth object, and it is the process many GPS satellites use. Essentially, when we know the distance from the tag to each anchor, we can draw a sphere with that distance as the radius around each anchor [11]. These spheres can only intersect at two points, and one of those points is the location of the tag (it becomes obvious which is the true location based on past data and where the field is located). Figure 6 shows a two-dimensional version of this graphically, where R_1, R_2, and R_3 are the anchors [12]. In our case, we will use the three anchors as the known points, and the distance measured by the DWM1000 modules will be used to calculate the distance between the tag and each anchor. With these distances, we can then use trilateration to calculate the precise location of the football on the field.

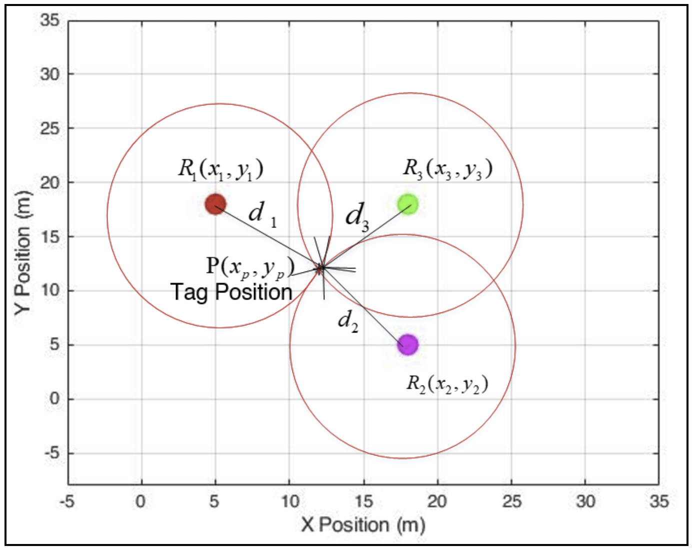

Fig. 6. Using trilateration to determine the location of a tag [12].

To send the location data from the tag's ESP32, we will use Bluetooth. The ESP32 will receive the calculated position of the football from the DWM1000, and then send this data to a nearby device, such as a smartphone or laptop, using Bluetooth. Below is the schematic for each anchor, consisting of one DWM1000 and an ESP32-Wroom-32. The tag will have the same components as well for this subsystem.

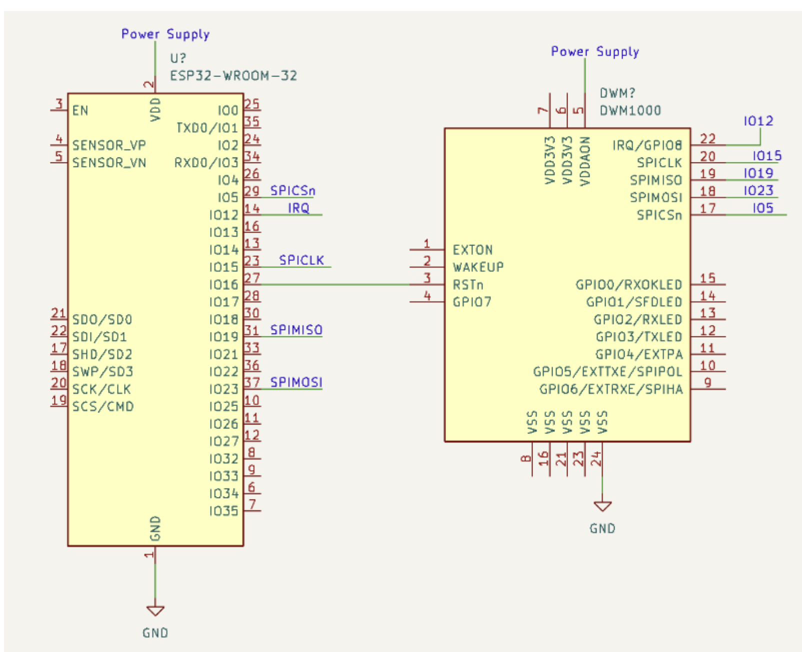

Fig. 7. UWB Anchor Schematic.

Requirements	Verification
• All UWB modules have current passing through them.	• Probe the input of the DWM1000 with voltmeter when batteries are connected to input and the Vout is maintained at constant 5 volts. After confirmation we use the ammeter to make sure that there is current coming from each of the output 3.3 volts
• Each anchor can communicate with the tag.	• Each anchor is tested one at a time. The tag is placed various distances away from the anchor, and we ensure that the correct distance is being recorded in the Arduino console, with an error of less than 10 cm.
• The football is correctly located.	• Place the football in various spaces throughout the field and measure its exact location with respect to the anchors. Then make sure that the program reports the same calculations with an error of less than 10 cm.
• Location data is sent back to the computer via Bluetooth.	• After ensuring that the correct data is being collected via wired transmission, see that Bluetooth allows the same data from the same location to be sent wirelessly, moving both the receiving computer and the football to different locations.

Table 3: Requirements and Verification for UWB Subsystem

2.3.4 Actuation

This subsystem will light up an LED indicating that our ball has either crossed the down marker, crossed the plane of the endzone, or crossed the boundaries of the football field for a touchdown. LEDs of different colors will be used in this module, with blue signaling a set of new downs, green signaling a touchdown, and red signaling out of bounds.

Requirements	Verification
• The correct LEDs must be lit up when the correct condition is met(i.e., touchdowns, new downs, out of bounds).	• We will use the Arduino IDE to program the PCB such that the LED colors above are lit up correctly.
• The LEDs must be lit up within one second.	• We will be using bluetooth technology that has a speed of 1 Mbps

Table 4: Requirements and Verification for Actuation Subsystem

2.4 Tolerance Analysis

The goal of our product is to be able to use our football in normal football play while still being able to track the location of the football to within 11 inches, as the size of an NFL regulation football range from 11 to 12 inches [4]. The football must be able to do this for the entirety of a football game.

2.4.1 Charging Capabilities

Our football's sensors must be able to last the full length of play of a football game. The longest ever football game lasted 82 minutes and 41 seconds. Therefore, to accommodate this time, the battery of our football must last at least four hours. According to the datasheet of the three components of our circuit, the ESP32, DW1000, and Bosch BNo055, the current draw of each of these parts is 240 mA [6], 13.5 mA [7], and 12.3 mA [5], respectively. The total current draw is 265.8 mA. As well, most of our components have an operating voltage of 3.3V-3.6V. A lithium-ion battery is used in this design, and according to the datasheet of different 3.7V batteries, most commercial lithium ion batteries will be able to output 0.2[8] of the total current capacity for four hours. Therefore, a 2000 maH 3.7 V battery will be able to serve our purpose if attached to a resistor load.

2.4.2 Football Load

Another consideration is the wear and tear of football play on the product. Since football is a contact sport, there are many different forces acting on the ball, such as a defensive back impacting the ball carrier, throwing and catching the ball, and even kicking the ball. The greatest force experienced by the ball will be during a punt. Most punters agree that for a successful punt, the time of the punt must be equal or greater to the distance of the punt divided by ten [13]. It is known that since a punt traces a parabolic arc, the starting velocity can be separated into a x component and y component. The x component, ignoring friction, will not be subject to acceleration. The y component will be zero at the peak of the parabola, or half the time, due to gravity (10.7171 yards per seconds squared). The x component squared plus the y component squared will therefore equal the total velocity. The three equations are given below, with the total velocities shown in Table 5.

$$V_x = distance / \frac{distance}{10} \tag{1}$$

$$V_y = \frac{seconds}{2} * 10.7171\, yards/seconds^2 \tag{2}$$

$$V_{total} = \sqrt{V_x^2 + V_y^2} \tag{3}$$

2.4.3 Chart Data

Distance (yards)	**Velocity (yards/seconds)**
10	11.34529
20	14.65819
30	18.93254
40	23.65271
50	29.5988
60	33.67141
70	38.82097
80	44.02048
90	49.25413
100	54.51208

Table 5: Distance vs Velocity

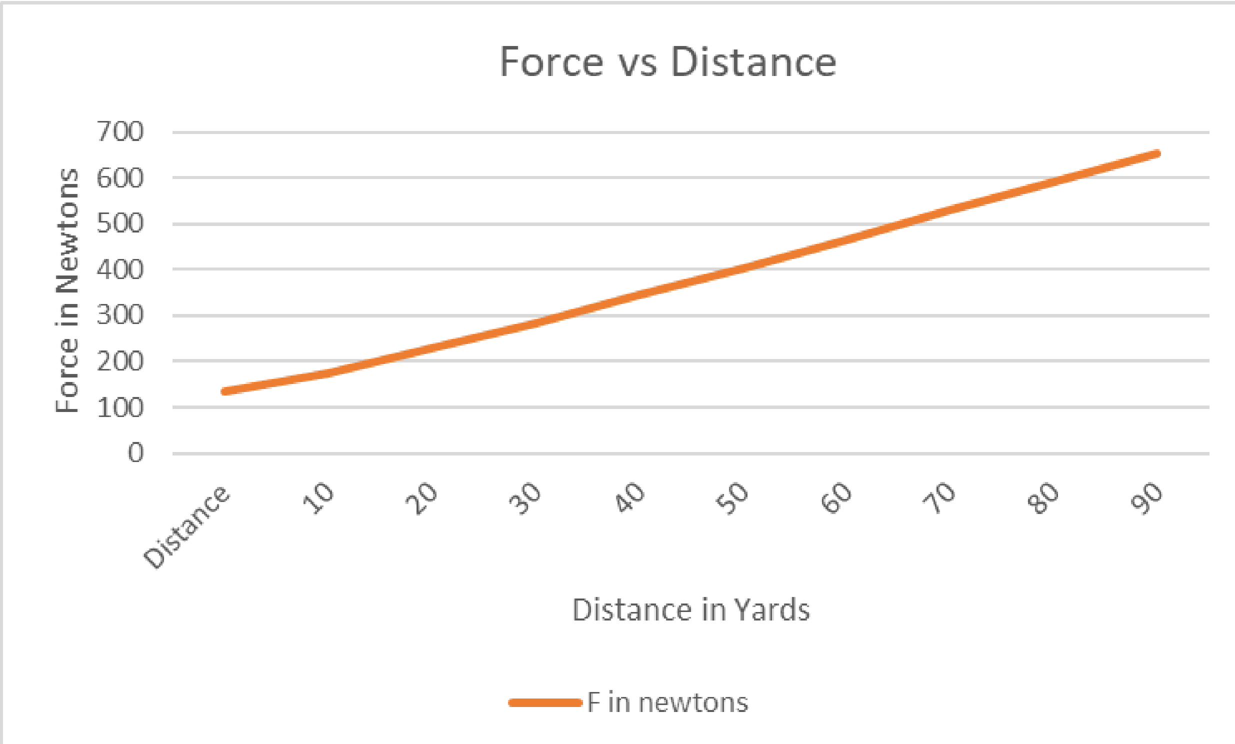

Fig. 8. Graphic visualization of force in newtons vs distance.

2.4.4 Analysis

Since it is difficult to find metrics on the average punter's kicking speed, we timed our own kick at .35 seconds. Since acceleration is simply velocity divided by time, we can use Newton's Second Law to get the force needed to kick the ball for these distances. Our final results are shown above in Table 5.

However, we know that there are many different factors affecting punts, such as friction and running speed before a punt. As well, a punter will be able to kick much faster than our group member. In fact, an average punter can kick the ball at about 2000 newtons, but the force at first contact can reach nearly 8900 newtons [14]. Because a kick impacts the ball in the middle, and our electronics will be at the center of the ball, this will be the force that our PCB must withstand. The other consideration are hits on the ball carrier. When hitting ball carriers, defensive backs can exert a force of up to 11000 newtons due to the mass and speed of both players [15]. Usually, the ball carrier's job is to protect the ball, but one collision that can directly impact the ball is the so-called "peanut punch," used to directly punch the football out of the ball carrier's hands. The average punch is about 2500 newtons [16], again usually on the center of the ball.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Parts

Part Description	Manufacturer	Part Number	#	Unit Cost($)	Total Cost($)
22µF Cap	Samsung	CL21A226MPQNNNE	6	0.18	1.08
.1µF Cap	Wurth Elektronik	885012207072	4	0.1	0.4
1µF Cap	Samsung	CL21B105KAFNNNG	3	.10	.30
10µF Cap	Samsung	CL21A106KPFNNNF	4	.19	.76
4.7µF Cap	Samsung	CL10A475KQ8NNNC	6	.1	.6
10k Resistor	Bourns	CRM0805-FX-1002ELF	24	0.39	9.36
180k Resistor	Vishay / BC Components	293-180K-RC	2	0.15	0.30
2M Resistor	Panasonic	ERJ-U02F2004X	2	0.12	.24
Dschottky-diode	Diodes Inc	SBR545SAFQ-13	2	0.52	1.04
espwroom32	Espressif Systems	ESP32-WROOM-32U-N16	2	4.35	8.70
dwm1000	Decawave Limited	772-DWM1000	2	16.67	33.34
usb_B_micro	POLOLU	USB MICRO-B CONNECTOR BREAKOUT BOARD	2	2.72	5.44
MCP73831-2-OT	Mouser	579-MCP73831T-2ACIOT	3	.76	2.28
TPS61200DRC	Texas Instruments	TPS61200DRC	2	2.72	5.44
32.768 khz crystal	Digikey	RT3215-32.768-12.5-TR	2	0.56	1.12
BSS138 MOSFET	Mouser	863-BSS138-G	2	0.53	1.06
MIC5225-3.3YM5-TR	Digikey	MIC5225-3.3YM5-TR	2	0.53	1.06

Table 6: Necessary Components

3.1.2 Manual Labor

Calculations for Manual Labor were calculated below. The following numbers are assumed

- Hourly Salary: $40
- Hours of work completed per week: 10 hours per week
- Total Weeks Worked: 16 weeks

With 3 people on this team:

(3 people) * ($40/hour) * (10 hours/week)* 16 weeks=$19,200

3.1.3 Total Cost

The total cost is. The calculations are as follows:

Total Material Cost + Total Labor Cost = 71.23 + 19,200 = **$19271.23**

3.2 Schedule

Week of	**Task**	**Person**
February 20	Finalize design and components	Everyone
	Order parts	
February 27	Start PCB design	Everyone
	Replicate schematics on breadboard	Everyone
	Begin to program sensor suite and Bluetooth	Akshay
	Begin to program UWB modules	Vibhav
	Test power and charging components	Varun
March 6	Finish preliminary PCB design and order	Everyone
	Continue programming UWB and sensor subsystems	Akshay and Vibhav
	Design enclosure	Varun
March 13	Test all components and programs on breadboard	Everyone
	Assemble PCB	Everyone
March 20	Test PCB and edit design as needed	Everyone
March 27	Finalize Changes for PCB order #2	Everyone
	Continue work on Enclosure to get ready for 3D printing; look into parts needed	
April 3	Work on 3D printing CAD design for PCB enclosure and purchase parts. Build enclosure for football and ensure weight is within specifications	Everyone
April 10	Fix any minor bugs	Everyone
April 17	Final presentation preparation	Everyone
April 24	Final Demo	Everyone
May 1	Final Presentation	Everyone

Table 7: Weekly Schedule and Task Allocation

4 Discussion of Ethics & Safety

While our product does not pose many issues in terms of physical safety, there are considerations we must take into account regarding the ethics surrounding this product. The main concern of our product is protecting the privacy of users, as well as maintaining competitive integrity among teams. Data integrity is of utmost importance to our firm. Maintaining standard data definitions, utilizing data encryption, and maintaining audit trails of our data practices are all methods we incorporate to ensure we adhere to the tenets mentioned in FDS Data Ethics Framework [17]. By making sure that our data storage remains secure, we align with the principles of the IEEE and ACM Code of Ethics, which call for promoting and upholding the dignity, privacy, and rights of all people, as well as avoiding harmful consequences [18].

References

[1] "American football vs rugby," *Diffen*. [Online]. Available: https://www.diffen.com/difference/American_Football_vs_Rugby. [Accessed: 23-Feb-2023].

[2] "Adidas reveals the first FIFA World Cup™ official match ball featuring Connected Ball Technology," *adidas News Site | Press Resources for all Brands, Sports and Innovations*, 01-Jul-2022. [Online]. Available: https://news.adidas.com/football/adidas-reveals-the-first-fifa-world-cup--official-match-ball-featuring-connected-ball-technology/s/cccb7187-a67c-4166-b57d-2b28f1d36fa0. [Accessed: 23-Feb-2023].

[3] "UWB in basketball," *KINEXON*. [Online]. Available: https://kinexon.com/blog/why-ultra-wide-band-technology-has-been-scoring-points-in-basketball-for-years/#:~:text=A%20big%20plus%3A%20In%20contrast,in%20all%20directions%2C%20including%20height. [Accessed: 23-Feb-2023].

[4] "American Football Sizes: Ball Size Chart: Net World Sports." *American Football Sizes | Ball Size Chart | Net World Sports*, https://www.networldsports.co.uk/buyers-guides/american-football-size-chart#:~:text=How%20big%20is%20an%20American,(396.89%2D425.24g).

[4] Inpixon. "Ultra-Wideband (UWB) Positioning & Sensor Technology." *Inpixon*, https://www.inpixon.com/technology/standards/ultra-wideband#:~:text=Ultra%2Dwideband%2C%20or%20UWB%2C,between%20devices%20through%20radio%20waves.

[5] Townsend, Kevin. “Adafruit BNO055 Absolute Orientation Sensor.” *Adafruit Learning System*, Adafruit, https://learn.adafruit.com/adafruit-bno055-absolute-orientation-sensor/downloads.

[6] Espressif, “ESP32-WROOM-32U,” ESP32 datasheet, Nov. 2017 [Revised Feb. 2023]

[7] Decawave, “DWM1000 IEEE 808.15.4-2011 UWB Transceiver Module,” DWM1000 datasheet, Feb. 2014 [Revised June 2016].

[8] PKCELL, “Li-Polymer 803860 2000mAh 3.7V with PCM,” Battery datasheet, June 2014.

[9] “Li-Ion Battery Charging Circuit Design - Kicad 5 [QCB 2].” *YouTube*, YouTube, 17 Dec. 2018, https://www.youtube.com/watch?v=GRd9uTwg7r4.

[10]Lan_Makerfabs and Instructables, “ESP32 UWB indoor positioning test,” *Instructables*, 30-May-2022. [Online]. Available: https://www.instructables.com/ESP32-UWB-Indoor-Positioning-Test/. [Accessed: 23-Feb-2023].

[11]GISGeography, “How GPS receivers work - trilateration vs triangulation,” *GIS Geography*, 31-May-2022. [Online]. Available: https://gisgeography.com/trilateration-triangulation-gps/. [Accessed: 23-Feb-2023].

[12]Poulose, Alwin & Han, Dong. (2020). UWB indoor localization using deep learning LSTM networks. Applied Sciences. 10. 6290. 10.3390/app10186290.

[13] "Football hang time," *rookieroad.com*. [Online]. Available: https://www.rookieroad.com/football/statistics/hang-time/. [Accessed: 23-Feb-2023].

[14] N. O'donnell, "How to: Kick a field goal (Robbie Gould Style)," *Chicago Magazine*, 06-Jul-2007. [Online]. Available: https://www.chicagomag.com/chicago-magazine/november-2006/how-to-kick-a-field-goal-robbie-gould-style/. [Accessed: 23-Feb-2023].

[15] M. Higgins, "Football physics: The anatomy of a hit," *Popular Mechanics*, 21-Jun-2022. [Online]. Available: https://www.popularmechanics.com/adventure/sports/a2954/4212171/. [Accessed: 23-Feb-2023].

[16] "Punch Force - the science behind the punch," *Boxing Science*, 18-Nov-2021. [Online]. Available: https://boxingscience.co.uk/science-behind-punch/#:~:text=The%20higher%20the%20Newton%20(N,about%203.5%20times%20body%20mass. [Accessed: 23-Feb-2023].

[17]"Federal Data Strategy Data Ethics Framework." [Online]. Available: https://resources.data.gov/assets/documents/fds-data-ethics-framework.pdf. [Accessed: 24-Feb-2023].

[18]"IEEE code of Ethics," IEEE. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.