ECE 445 Spring 2023 - Design Document

Footballytics

Team 16

Vibhav Adivi (vadivi2)

Akshay Bapat(aabapat2)

Varun Venkatapathy (vcv2)

Professor: Victor Gruev

TA: Xiangyuan Zhang

May 3, 2023

Abstract

FIFA and the NBA have designed technologically advanced balls to increase precision in training and gameplay, but no such work has previously been done in American football. Footballytics is a project that implements location and motion tracking into a football to get more accurate statistics. This paper discusses the design and implementation of Footballytics, and the result of this was a system that is able to track the location and motion of the product and display that data visually.

Contents

1 Introduction

1.1 Problem and Proposed Solution

In American football, crucial calls, such as determining the spot of the ball, rely solely on human sight. Because of this subjective nature of the sport, the accuracy of some rulings has come into question during key matches. Meanwhile, FIFA and the NBA have implemented balls [1][2] sporting cutting-edge sensory equipment allowing coaches to track ball movement and analyze player performance. Our team believes that a solution is needed to address the inaccuracy and subjectivity in football. In addition, balls can get deflated over the course of the game, so pressure in the ball needs to be monitored as well. Therefore, we set out to solve these issues.

Footballytics is our solution to combat the inaccuracy that athletes may face during gameplay. With Footballytics, we devised a system that can collect movement and location data and send that data back to a computer using Bluetooth, where the data can be visualized and analyzed in real time.

1.2 Visual Aid

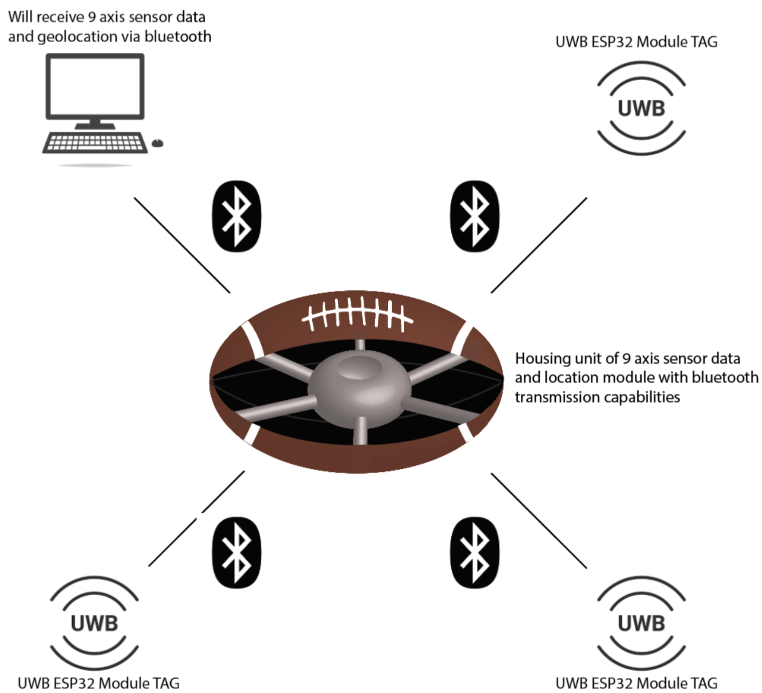

Fig. 1. Overview of the Footballytics Device operating in conjunction with UWB anchors for geolocation tracking.

1.3 Original High-Level Requirement List

The following list is the criteria we initially wanted to focus on.

- 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 [3]. The sensor will be able to withstand pressures up to 20 psi which will enable the sensor to provide accurate real-time readings.

1.4 Block Diagram

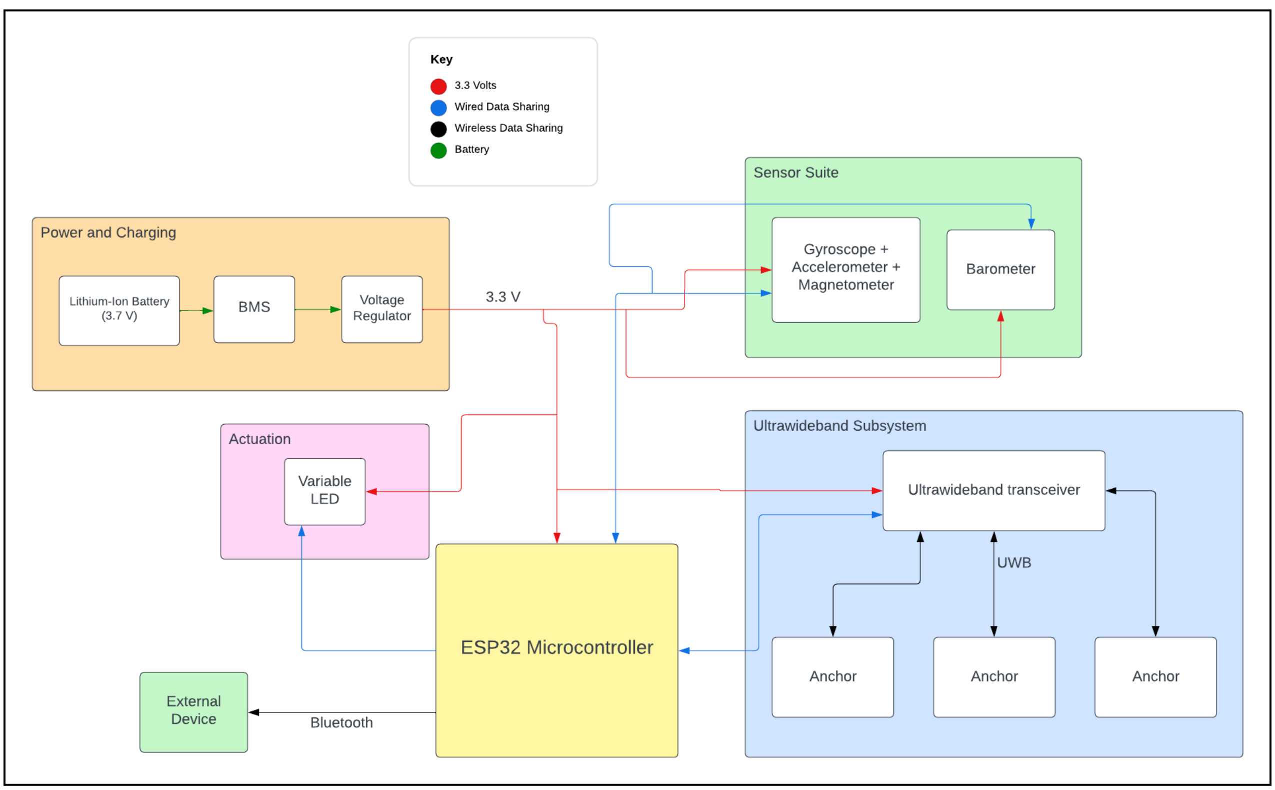

Fig. 2. Block diagram of system.

2 Design

2.1 Sensor Suite

2.1.1 Design Procedure

The original design of this subsystem consisted of a 9-axis inertial movement unit with an accelerometer, a gyroscope, and magnetometer, as well as a barometric sensor. Our final product did not utilize the barometric sensor, so this subsystem only had the 9-axis IMU to track these metrics of the ball. Alternatives include the 6-axis IMU which would not have had the magnetometer, and only relying on the location data to tell us about movement rather than using a separate sensor. We opted for the 9-axis IMU because it would give us the most accurate movement data in conjunction with the location data. In conjunction with the movement sensor, we also wanted to track the pressure inside the football, but this was not implemented in the final design because we were not able to get the part we ordered to work with our system and chose not to prioritize it.

2.1.2 Design Details

Our original design utilized the Bosch BNO055 IMU and the BMP581 barometer to fulfill the requirements of the sensor suite. Both of these were to interact with the ESP32 microcontroller using I^2C protocol at 3.3 volts. As recommended from the data sheet for the BNO055, the input was to have a 2.1μF capacitor and two 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 included MOSFET BSS138, and has resistors placed in series. For a visual reference refer to Figure 3.

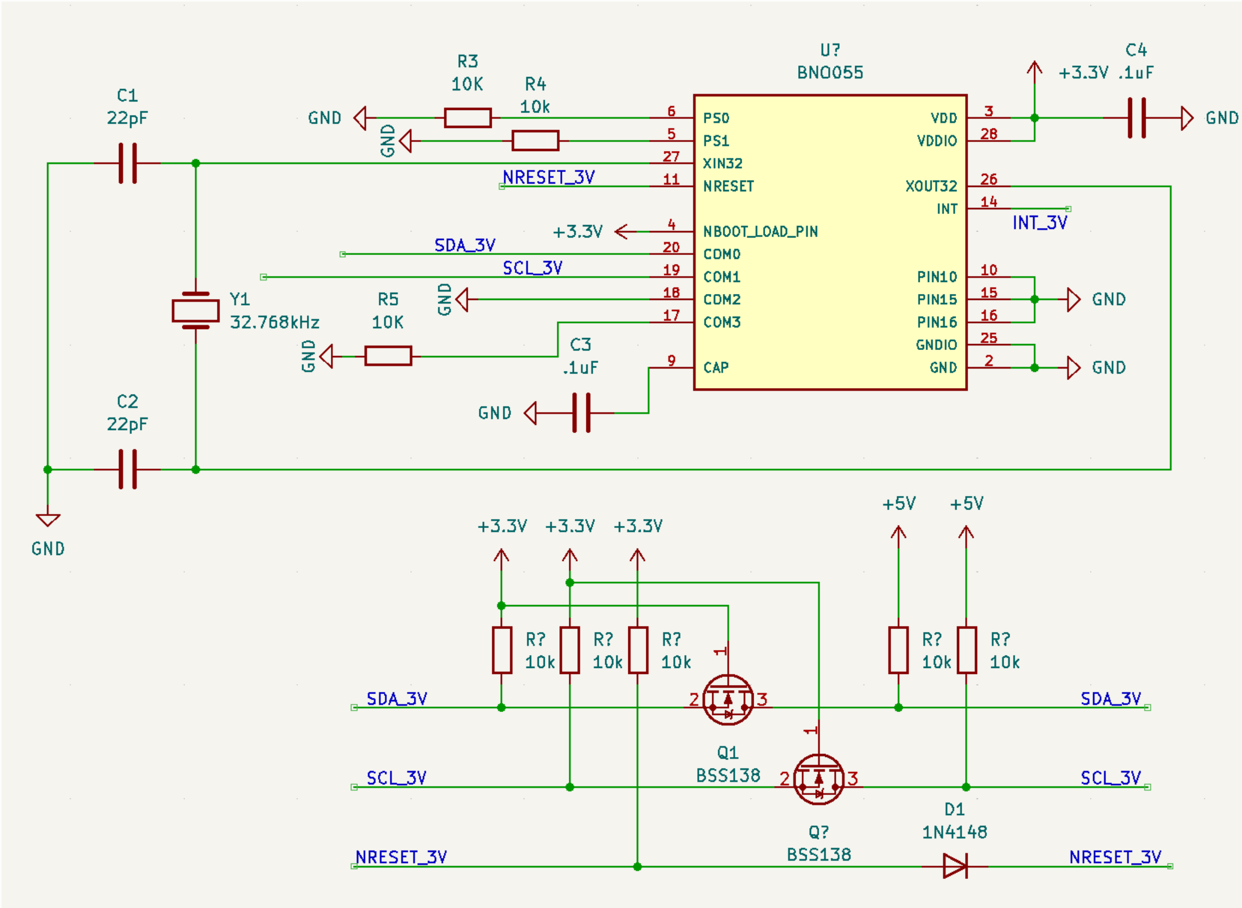

Fig. 3. Sensor Suite [4]

Because of the issues with our PCB order, we ordered another 9-axis IMU, because the BNO055 was not functional on a breadboard. This was the SparkFun ICM-20948 breakout board. We powered this at 5 V from the ESP32, and it was also connected through the I2C protocol.

2.2 Power and Charging

2.2.1 Design Procedure

This module was to provide rated current for all the modules of our PCB at 3.3 volts. It needed 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 was to last at least four hours to accommodate any uncontrollable circumstances. Since our microcontroller, UWB module, and sensor module have current draws of 240 [5], 13.5 [6], and 12.3 [4] mA, respectively, a battery must be rated for at least 265.8 mAh with a capacity of four hours. Alternatives included a non-rechargeable battery or powering by microUSB, but in our initial design, we thought a rechargeable system would be most optimal because of how a football is packaged. In the final design, we opted to use microUSB power sources for the components instead of a battery because we were unable to implement the necessary rechargeable circuit without a proper PCB. The three anchors were plugged into wall outlets, and we used a mobile power bank for the tag.

2.2.2 Design Details

This module had three parts: a USB-micro charging port, a charging circuit to allow our battery to recharge, and a 3.7V battery with a current output of 2000 mAH. The plan was to use a Micro-USB port to actually provide voltage to our battery, as Micro-USB is very common and we would have been able to charge from any computer. We also designed a circuit to recharge our battery, given some external voltage. We chose to 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. This was all to be done in conjunction with a lithium-ion battery rated at 3.7 volts and 2000 mAH. From above, we know that our parts had a total current usage of 322.3 mAH. Most batteries are tested to last for four hours at 20% capacity [7], so in this case 20% of 2000 is 400 mAH. In addition, since our parts were all rated from 3.3-3.6V, we planned to use two resistors in series to slightly bring down the voltage. We chose to use one 400-ohm resistor and one 3300-ohm resistor, and output the voltage from in between the two resistors. The relevant schematic is Figure 4.

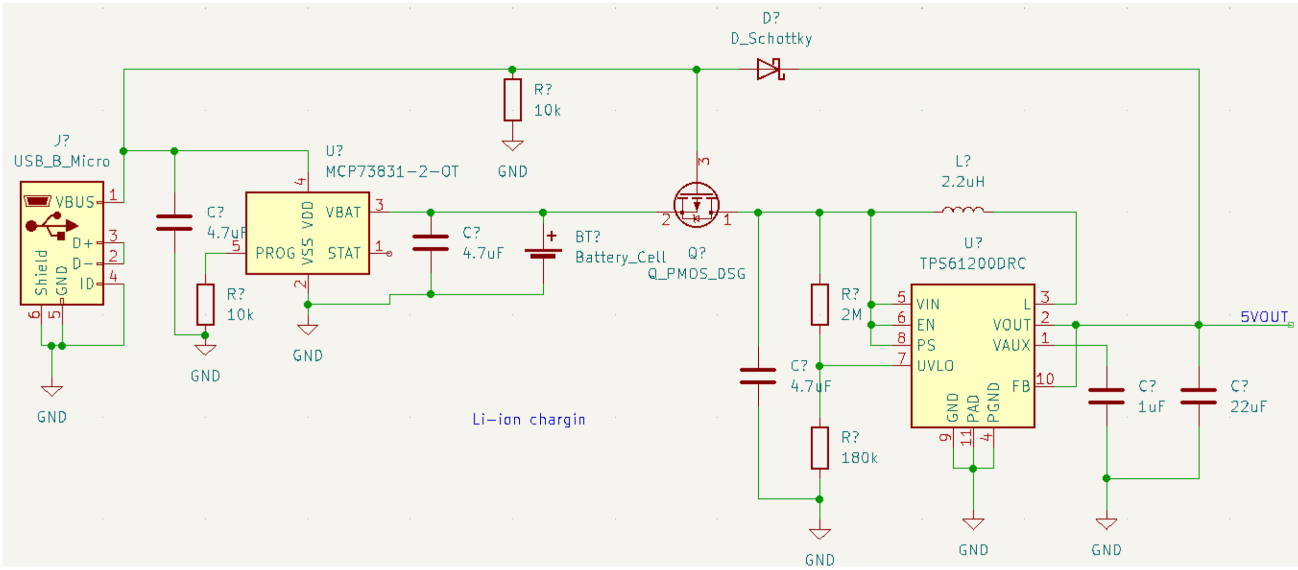

Fig. 4. Lithium-Ion Charging with Micro-Usb plug-in [8].

Because we did not get a PCB in time, we did not implement this system as originally designed. The microcontroller that we used was the ESP32-Wroom-32, and we chose to get a breakout board for this that already came with a microUSB port, so we powered our circuit through that using a power bank for the tag and wall outlets for the anchors.

2.3 Ultra-Wideband System

2.3.1 Design Procedure

The purpose of the ultra-wideband (UWB) subsystem is to accurately position the football in real-time. This subsystem consists of four UWB transceiver ICs, each connected to a separate ESP32 microcontroller in SPI protocol. Three of these are anchors placed around the field, and one of them is the tag inside the football. Using the known position of the anchors, the tag uses a time delay to calculate its distance from each anchor, and using these distances, performs trilateration to locate itself. We used a DW1000 UWB transceiver for this. 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 [6]. An alternative to UWB positioning is GPS tracking to find location in a more absolute way, but we decided to use UWB because GPS is accurate at a large scale while UWB is accurate at much smaller scales, closer to the precision we would need in this case.

2.3.2 Design Details

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 DW1000 is in the range of 3.5 to 6.5 GHz [6]. 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) [9].

By using three anchors with known positions, we used 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 circle with that distance as the radius around each anchor [10]. These circles can only intersect at one point, which is the location of the tag. Figure 5 shows a version of this graphically, where R_1, R_2, and R_3 are the anchors [11]. In our case, we will use the three anchors as the known points, and the distance measured by the DW1000 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.

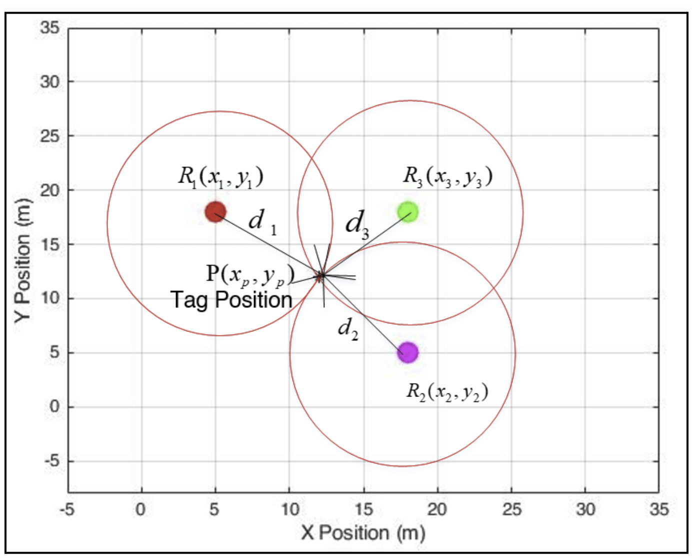

Fig. 5. Using trilateration to determine the location of a tag [11].

Figure 6 shows the schematic for each anchor, consisting of one DW1000 and an ESP32-Wroom-32. The tag has the same components for this subsystem.

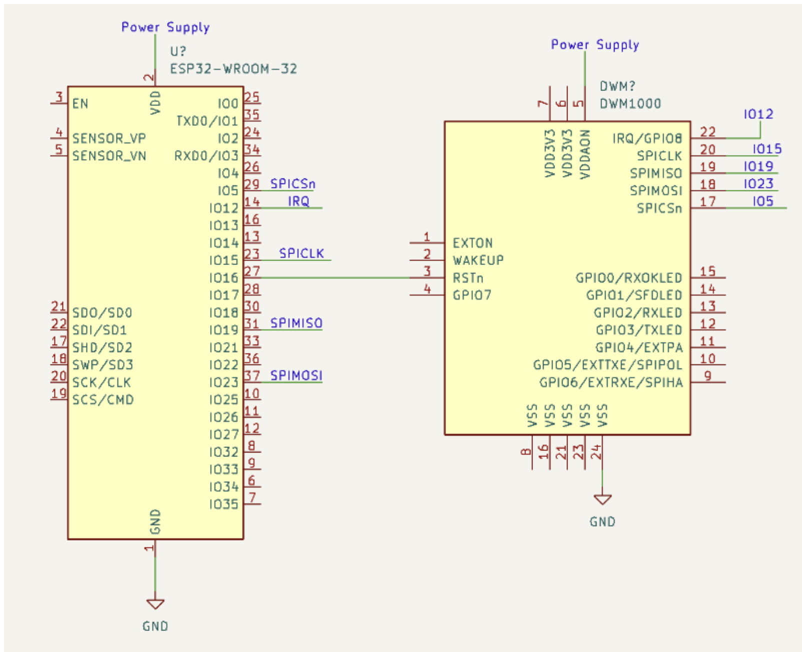

Fig. 6. UWB Anchor Schematic.

2.4 Actuation

2.4.1 Design Procedure

Our original plan for this subsystem was to have an LED light up, 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. We chose to expand this subsystem by sending the data to an external computer via Bluetooth and using that data to display a graphical representation of the location and motion of the tag using Python. There are many alternatives to this, like the aforementioned LED as well as a speaker, but we chose to use a graphic that could give more information about the activity of the ball. In addition, we chose to use Python and the library Matplotlib to display this instead of other programs and libraries because it was able to update the data in real time using data directly from the serial Bluetooth port. Figure 7 shows a screen capture of the graphic that shows the position of the tag with an anchor at approximately (0,0), (0, 4), and (5, 0).

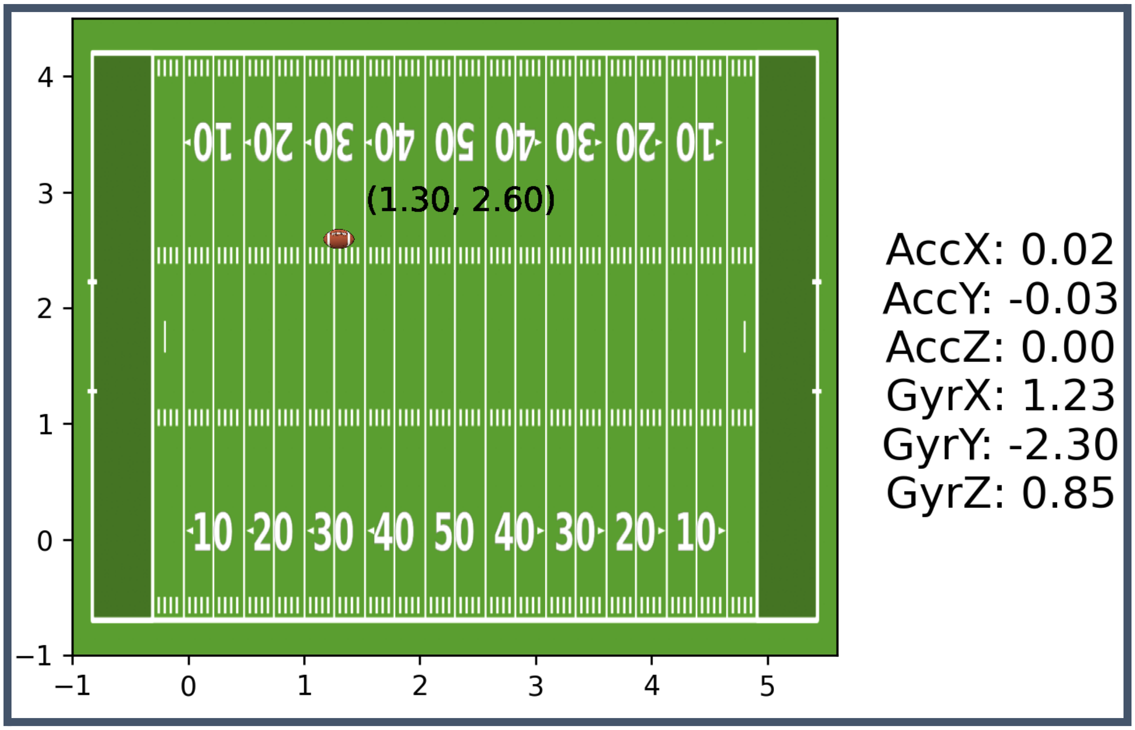

Fig. 7. Screenshot of Actuation from Python Program.

2.4.2 Design Details

We uploaded a program to the connected microcontroller that listens for the addresses of the anchors, calculates its distance from all three anchors, and prints them to the Bluetooth serial using the built-in Bluetooth on the ESP32-Wroom-32. Subsequently, the microcontroller collects the IMU and outputs the data in the same way, and both of these processes are performed repeatedly. The flowchart in Figure 8 shows this process.

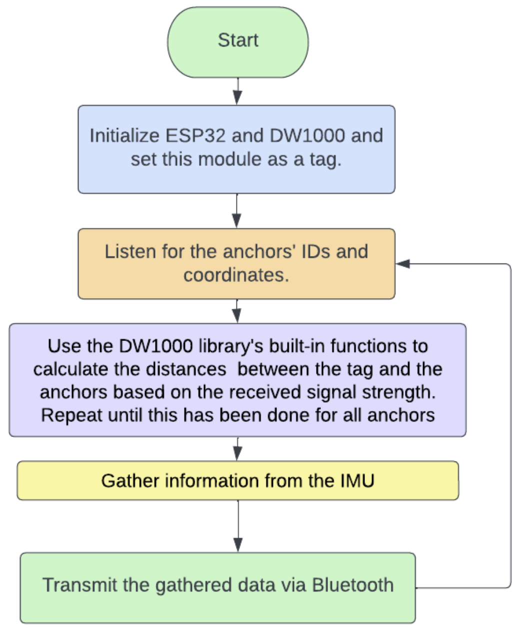

Fig. 8: Flowchart for Arduino Code.

Once the data is transferred via Bluetooth, the computer reads it as serial input to be used in a Python program to update the visual as shown in Figure 9.

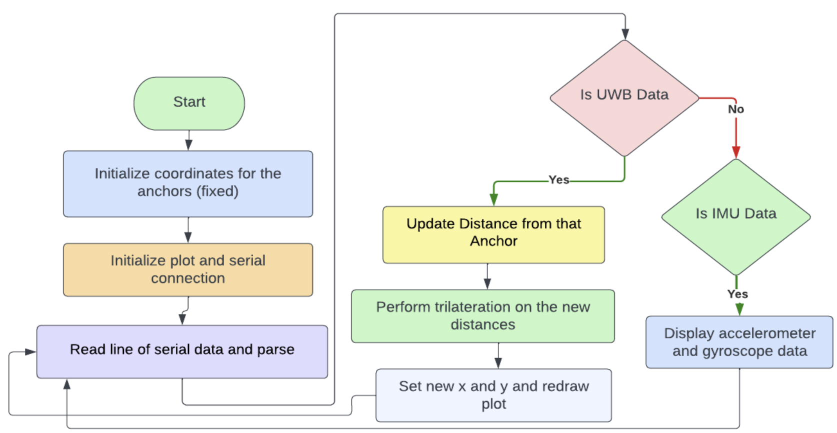

Fig. 9.Flowchart for Python Code.

3 Design Verification

3.1 Ultra-Wideband System

The ultra-wideband system and its verification constituted the bulk of the project. Since this subsystem is core to our product, it was necessary to have stringent requirements so that the location tracking would be as accurate as possible. Since our original requirements and verification table was already so extensive, there was no need to make any changes.

The first requirement was to make sure that the dev kit that was the tag could communicate with all three anchors. This requirement was also quite easy to verify because the distance from each anchor to the tag was able to be seen in the serial terminal.

The second requirement was to make sure the distance from the tag to each anchor is accurate to within 30 cm or the length of an American football. By checking the displayed value against selected distances on a tape measure, the accuracy of the tag distance could be seen. At first, the displayed distances were quite inaccurate compared to the real distance. However, the biggest factor to take into account was the antenna delay (Adelay) factor. The antenna delay factor is the time the anchor takes to transmit a packet to the tag added to the time to receive a packet back from the tag.

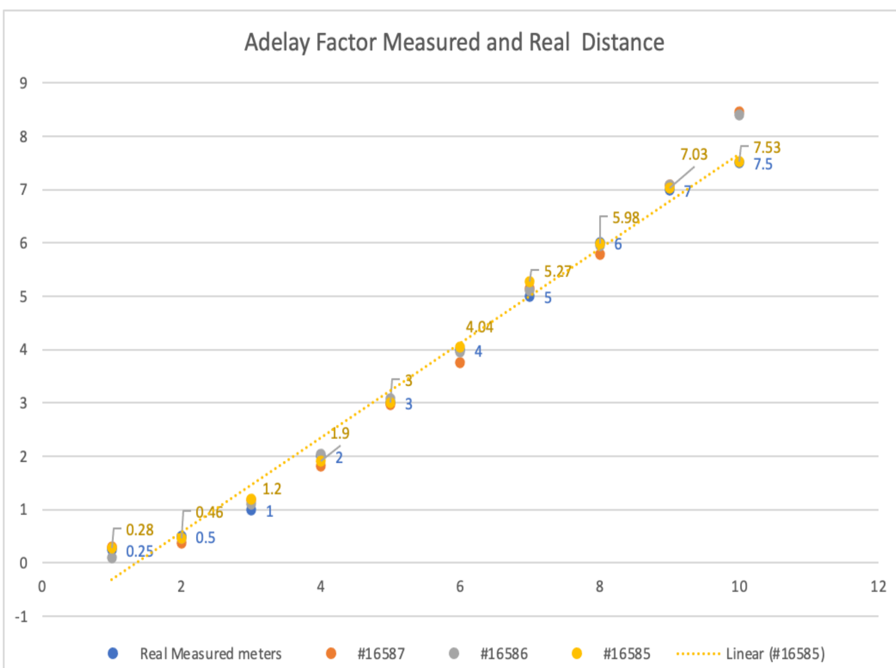

Fig. 10: Adelay Factor Distances vs. Real Distances.

Different Adelay factors displayed measurements and how they measure up against the real distance can be seen in the above figure. Since the demonstration did not take place in a football field, it was necessary to find the best Adelay factor for within 1 m to 4 m, which the Adelay factor of 16585 met.

Once the correct Adelay factor was found, the next requirement was making sure that the correct coordinates were displayed. Physically, this was done by placing the tag in a random place in the area designated by the three anchors. Then, both the X and Y were measured from the anchor designated as (0, 0) in the coordinate plane. Figure 7 shows that the coordinates are being displayed, but one thing that is not being shown is the fact that these coordinates fluctuate. By taking seven readings and averaging them over one second, the fluctuations decrease to within 30 cm, so that the location tracking is accurate enough for the purposes of football.

3.2 Sensor Suite

The sensor suite consists of an accelerometer and gyroscope, without the barometer. The requirement for the accelerometer was that it reflected accurate values to within .05 m/s^2. The accelerometer had units of milli-Gs, and when converting the values at standstill to m/s^2, in the z-direction, an acceleration of 9.6-9.8 m/s^2 was seen. This matches what is expected, as the accelerometer is measuring the force of gravity. To further verify the accuracy of the accelerometer, the tag was moved in all three axes for one meter and timed for three seconds. The X was .337, Y was .338, and Z was .332, so the displayed values were all within .05 m/s^2 of the expected values.

The other part of the IMU was the gyroscope. The requirement for this sensor was that the readings were accurate to within 5 degrees per second and reflected the correct directions. This was easily done by tilting the tag in all three directions 90 degrees and timing the tilt for one second measured against a protractor. It was seen that in all three directions, the displayed values were 92.4 for X, 87.8 for Y, and 89.7 for Z, which means that the gyroscope passed verification.

3.3 Actuation

This module was changed the most from the original. The original actuation simply involved three LEDs that would light up when certain conditions were met, whereas now, the actuation is a real time visualization of the ball. Therefore, the first requirement here is that the visualization accurately reflects all cases of the ball moving around. This was verified by moving the ball within the bounds of the anchors, where on screen, the ball accurately reflected where the ball was going. As well, if the ball left the bounds, then the ball on the screen would disappear. This also proved true.

The second requirement of actuation is actually something that remained common between the original actuation and now. Since the end product is going to be a ball that can be played on a field, it has to use Bluetooth technology to remain modular and still send data to a computer. Therefore, the requirement is that the tag can use Bluetooth to send data and still hold the same accuracy. When the tag was removed from the computer and attached to a battery pack, none of the values being displayed took a hit in accuracy, and the real time capabilities of the visualization remained unchanged, so this requirement was a success.

4 Costs and Schedule

4.1 Costs

4.1.1 Parts

Table 1 is the list of parts and their costs that we would have used had our PCB come in as planned. We did get these parts but did not end up using them.

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 1: Necessary Components for finished PCB.

Table 2 shows the parts we ended up using for the demo

Part Description	Manufacturer	Part Number	#	Unit Cost($)	Total Cost($)
ESP32 + UWB Development Board	Makerfabs	ESP32UWB	2	39.80 + tax + shipping	187.10
Sparkfun 9DOF IMU	Sparkfun	SEN-15335	1	18.50	18.50
HiLetgo BME280 3.3V Atmospheric Pressure Sensor	HiLetGo	3-01-1231-A	1	9.49	9.49

Table 2. Parts for demo.

Table 3 shows the parts needed for the enclosure of the system.

Part Description	Manufacturer	Part Number	#	Unit Cost($)	Total Cost($)
PRO White Classic American Football Lace	PRO Lacing Products	N/A	1	11.99	11.99
Maine Thread - .030" Standard Pack Waxed Polycord	Maine Thread	WP-STD.PK-.030-6	1	18.50	18.50
Gorilla Removable Mounting Putty	Gorilla	N/A	1	15.00	15.00
M-D Building Products 2006 M-D 0 Open-Cell Air Conditioner Weather-Strip	M-D Building Products	N/A	1	2.93	2.93
Electrical Project Case	Zulkit	2019008905	1	11.99	11.99
White Ceiling Hook KIT	Romeda	N/A	1	6.98	6.98
Encore Series Football	Wilson	N/A	1	24.99	24.99

Table 3. Necessary Components for Enclosure.

4.1.2 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

4.1.3 Total Cost

The total cost if we had had the PCB is as follows:
Total Material Cost + Total Labor Cost = 71.23 + 92.38+ 19,200 = **$19,361.61**

The total cost for what we showed in demo is as follows:
Total Material Cost + Total Labor Cost = 215.09 + 92.38+ 19,200 = **$19,507.47**

4.2 Schedule

Week of	Task	Person
February 20	Finalize design and components	Everyone
	Order parts	
February 27	Start PCB design	Everyone
	Polish schematic for UWB	Vibhav
	Work on schematic or sensor suite	Akshay
	Improve schematic for power and charging	Varun
March 6	Continue working on PCB Design	Everyone
March 20	Test PCB and edit design as needed, send out our first order	Everyone
March 27	Start designing enclosure	Varun
	Attempt to breadboard parts, trying to solder pins onto parts to test on breadboard	Akshay and Vibhav

April 3	Find out our PCB is delayed	Everyone
	Order development boards for the main components	Everyone
April 10	Get the boards to test the UWB system	Vibhav and Varun
	Start testing sensor suite	Akshay
April 17	Finish polishing all the systems and write the actuation	Everyone
April 24	Final Demo	Everyone
May 1	Final Presentation	Everyone

Table 4. Schedule of Project Development.

5 Conclusion

5.1 Accomplishments

Our team has achieved several significant landmarks in developing our device for football tracking. One of our biggest achievements was having the location tracking accurate up to 30 cm, which is the length of a football. This level of precision and accuracy becomes very important when tracking ball movement during the game.

Another significant accomplishment was having our device read accurate Inertial Measurement Unit (IMU) data. The IMU would allow us to detect when the device is moving in any direction and when it is not. Using the accelerometer data and gyroscope data would allow us to gauge movement of the ball.

Furthermore we have successfully implemented Bluetooth connectivity. This was a big requirement in our project as it was essential to transmitting data during the game as the football needs to be completely wireless. This accomplishment has ensured that our device can transmit data reliably and efficiently, providing real-time feedback to coaches and players during the game.

Overall our team has made a great effort in creating reliable and accurate devices for tracking football movement. We are excited to continue refining our technology in the field of sports.

5.2 Uncertainties

Our failures in our project came from many unexpected difficulties with our PCB design. We had originally submitted our PCB order in the Week 2 order and had sent it to a different TA as we were told any TA can submit our PCB order. 4 weeks into the design process he had told us that he had “forgotten” to submit our PCB order and lied about submitting it after the fact. Because of this issue we had received our PCB in the final round of orders. This meant that we could not get any of our parts soldered onto the PCB board. Because of the PCB order issue we were also not able to implement our rechargeable battery aspect of our design. Seeing how this was a less important requirement in our project we decided to focus more upon the geo tracking and motion sensing instead.

5.3 Ethical Considerations

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 [12]. 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 [13].

5.4 Future Work

Many different adaptations, tests, and experiments have been left to be continued in the future because of the lack of time we had for this project since experiments with real-time data collection is an exhaustive and lengthy process. Future work on this project would relate to exploring deeper applications of the technology we have created.

The following ideas could be tested:

1. It would be interesting to apply our metric collection technology and have it be even more personalized. By having each player wear a tag whenever the football device reads a player with a tag the device will associate all relevant metrics with the player. For example if the player throws the football, we will be able to track how far that specific player was able to throw, what angle it was thrown at, what speeds, etc. Such metrics will allow coaches to train their players more effectively by having access to such data.
2. Our computer based simulation model could also be changed. Instead of having the data visualized and sent to a local computer we could implement a web application that can be accessed on any device. Web applications are easily accessible from anywhere making it convenient for our audience to access these metrics. Further, it is easy to update since all web apps are hosted on a server. Once the application is updated, all users accessing the app will instantly see the latest version.

References

[1] "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].

[2] "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].

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

[5] Espressif, "ESP32-WROOM-32U," ESP32 datasheet, Nov. 2017 [Revised Feb. 2023]

[6] Decawave, "DWM1000 IEEE 808.15.4-2011 UWB Transceiver Module," DWM1000 datasheet, Feb. 2014 [Revised June 2016].

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

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

[9]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].

[10]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].

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

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

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

Appendix 1 Requirements and Verification Tables

The below tables show the tables from our design document as we initially intended to test our system.

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 A1: Requirements and Verifications for Sensor Suite

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 A2: Requirements and Verification for Power and Charging

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 A3: Requirements and Verification for UWB Subsystem

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 A4: Requirements and Verification for Actuation Subsystem