Delft University of Technology
Master’s Thesis in MSC: Embedded Systems

Virtual Referee - A system to identify offsides in Football

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Title

Virtual Referee - A system to identify offsides in Football

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Abstract

The off-side rule is the most complicated rule in soccer. Today, off-sides are determined with the help of referees running on the sides of the field or with the help of cameras. However, for lower league games the installation of a camera based system is very expensive.

This work proposes a sensor based system that can be worn by players which can automatically detect off-sides. In order to create such a system, two aspects had to be researched (a) localisation and (b) ball detection. This work provides an evaluation of an ultra-wide band system in outdoor conditions to solve the localisation problem and various proximity based sensors to solve the ball detection problem. The primary research objective of this work was to find the pit-falls of the ultra-wide band system with respect to our application. It was found that the tri-lateration algorithm implemented on the devices contributed to a lot of errors in localisation accuracy and the overall system suffered from significant packet loss.

A custom tri-lateration algorithm along with hardware improvements are proposed. Our results show that the localisation errors are reduced by 56 % and improved system suffers from nearly no packet loss. As for ball detection, results show that ToF sensors provided the best accuracy in detecting the ball.

Preface

This thesis marks the end of my student journey of 20 years. The last 12 months have proved to be a major learning experience. I am also deeply overjoyed that this thesis is a culmination of an idea that I wanted to implement for a long time.

I would like to first start by thanking Marco Zuniga, my supervisor. Right from helping me write a proposal to make this thesis a funded project to having numerous technical discussions, he has constantly supported and motivated me throughout the period of my thesis. I would like to express my gratitude to Arjan van Genderen for becoming my external defence committee member on a very short notice. To Ioannis, Eric and Casper for giving me valuable suggestions and helping me conduct experiments. I would also like to thank the University Funds and TU Delft Alumni for helping me realise this project.

During the period of my masters course, I have made many wonderful friends. I would specially like to thank Chaitra, Meghana and Vineet for helping me with my elaborate experiments. Finally, to my parents for making me what I am today and for backing me through all the difficult times, this thesis is for you as much as it is for me.

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Chapter 1

Introduction

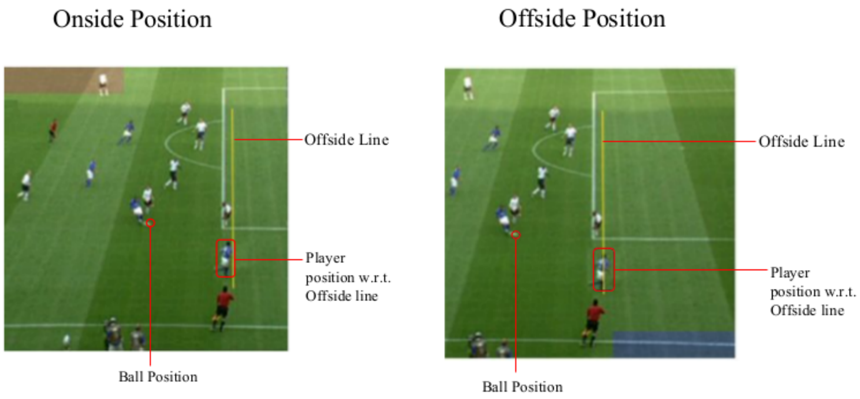
1.1 Motivation

Ever since its invention in the mid 19^{th} century England [3], soccer also known as association football has grown exponentially to become today's most popular sport. The game is played by 250 million players in over 200 countries [6]. There are about 17 rules of the game published by FIFA to ensure an agreement of understanding of the game amongst players.

One of the most complicated rule of football is the *Offside Rule*. In short, a player is in the offside position if the ball is played forwards to the player in the opposition team's half and there is no other player between that player and the opponent's goalkeeper [7].

The offside rule was made in order to prevent players from lingering around the opponent team's goalpost. It is enforced to make the goal scoring process more challenging and make the game more exciting. Figure 1.1 describes two scenarios of players standing in different positions of the field while playing one where the attacking opponent is in the offside position and the other where the attacking opponent is onside.

These offside goals have a tremendous impact on the team it is scored against. This can be detrimental to team moral. An example of such a case at the highest level of the football was the game between Manchester United and Liverpool in the 2014 Premier League game. Juan Mata scored a second goal against Liverpool which happened to be an offside. The game concluded with Liverpool losing 0 - 3 to Manchester United and narrowly missing out on their Premier League title [4].



(a) Player in Onside position.

(b) Player in Offside position.

Figure 1.1: Offside decision with respect to the second last opponent

1.2 Problem statement

The offside rule is enforced by the *linesman*. He/she is third official that aids the referee from the sideline, especially to see if the ball is out of play.

Works like [8] and [14], use many cameras and complex image/computer vision algorithms to automatically *locate* different players on the field and detect off-sides. Furthermore, employing complicated image processing and computer vision algorithms rely on a lot of training data, which is mostly available for professional level games. Realising these solutions may be possible in pro league games but in small community friendlies, the solutions are hardly feasible.

Sensor miniaturisation has seen a tremendous progress in the wearable sector. One work [13], studied the adoption of various types of sensors in wearable forms to improve the performance in athletes. The study also gave a broad overview of the different types of sensors employed to measure physiological signals, movement and posture data; all which can help an athlete improve his/her game.

In this thesis, we would like to further examine if the combination of data from different sensors in a wearable device can be used to make game decisions like identifying off-sides in football. Specifically focusing our attention on detecting off-sides, we would need to know where the football players are on the pitch and which player has the ball or is involved in the play when the off-side has occurred. The questions we would like to answer in this thesis are

1. Which of the location based sensor technologies is best suited for identifying different player positions on the field? Given a set of requirements, what are there practical shortcomings of employing such a technology for this particular application?
2. Can we identify which player has the ball solely based on the information obtained on his/her movements rather than having any sensor inside/on the ball?

The goal of this project is to develop a wearable sensor system to be worn around the player's shin that can automatically detect offside scenarios in football without the need for cameras around the field or sensors inside/on the football.

1.3 Contribution

This work presents a sensor based system to detect for possible offside scenarios in football. It also gives rise to the following contributions:

- A sport platform comprising of different sensors interfaced with a processing unit and logging facility, capable of capturing the data from players.
- Evaluated the performance of localisation system in outdoor environment. The shortcomings were analysed through a reverse engineered tri-lateration algorithm.
- An improved tri-lateration algorithm which shows an improvement in location accuracy by 56 % was realised.
- Evaluated different sensors for ball detection.

1.4 Thesis organisation

Chapter 2 presents the current state of the art solutions used for detecting off-sides in football and an overview on different localisation technologies and techniques. Chapter 3 presents the requirements and a brief overview of the prototype implemented. An evaluation of the current Ultra-wide Band system, analysis of its pitfalls and suggested improvements are mentioned in Chapter 4. Chapter 5 explains the evaluation of various proximity based sensors for ball detection. Experimental results of the implemented system is presented in Chapter 6. Lastly, the conclusion is presented in Chapter 7.

Chapter 2

Background

This chapter describes the basic building blocks and concepts required for understanding the work done in this thesis. Section 2.1 provides an overview of the state of art systems. Sections 2.2 and 2.4 divides this thesis into two basic blocks and provides an overview of the same.

2.1 State of Art Systems

The following are some of the state of the art systems currently employed in the detection of off-sides in soccer.

1. *Video Assistant Referee:* It is the most popular technology currently used in pro-league matches. This system comprises of a lot of cameras mounted around the field. During the game if the referee feels that the goal might be off-side, he/she signals for a review. The footage of the game is then immediately played back by a control centre and a final decision is issued. This system has two disadvantages (a) it is very expensive (about 6.2 million dollars) [5] (b) the reviews add a lot of extra time to the game.

2. *Catapult Sports:* The most commonly used location trackers used by football clubs during their training sessions.The device consists of a GPS module and an accelerometer. It gives insights about player performance during training sessions. However, it is not employed to make game based decisions.

3. *Zebra RFID:* Another popular localisation technology employed predominantly in the American football. It employs active RFID tags which are mounted on the player's protective gear, to track him/her. The ball also consists of an active tag for reporting its position. This

system has been used by teams to make strategic substitution changes during the game. The drawbacks of this system are (a) sensors need to be installed inside the ball, (b) an active RFID reader must be placed on the sides of the field which is expensive.

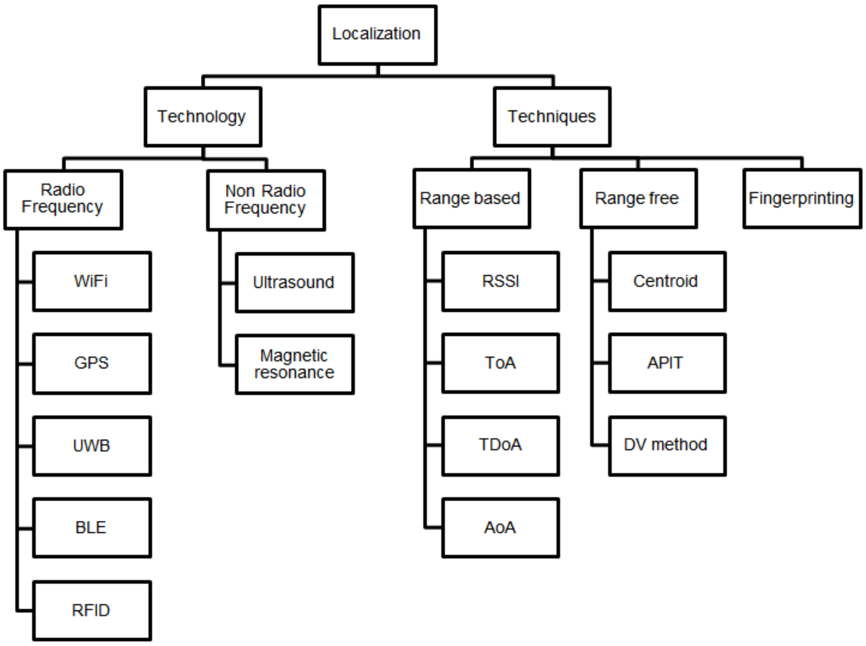


Figure 2.1: Classification of Localisation Systems

2.2 Localisation Systems

A localisation system is a mechanism for determining the position of an object in space. This section will try and give some background information on the various localisation systems. This includes presenting a broad overview on the techniques, technologies and classify them in a logical fashion.

Localisation system can be classified by (1) the underpinning Technology and (2) the techniques used by the localisation technology. Fig 2.1 shows the classification structure.

1. *Technology:* The technology providing localisation can be sub classified into RF based technologies like WiFi, Bluetooth, UWB and non RF based systems such as cameras, light, IMU etc. As most modules are RF enabled, we will only limit our scope of comparison to RF based technologies which are further discussed in the subsequent section of

this thesis.

2. *Techniques:* There are many techniques which are employed by different technologies in order to give a position estimate in a given space. These techniques can be classified into range based, range free and fingerprinting methods.

   Range based methods are those in which the object to be localised, ranges itself to a set of fixed reference nodes and reports its position w.r.t. the reference nodes. Range free methods are those which do not depend on distance estimation from a fixed reference frame.

   Fingerprinting are those methods that capture the state of a signal at different parts of the area under consideration. Both range free methods and fingerprinting methods give us a rough estimate of where the object may be in space. In order to get the precise position estimate, we rely on range based methods which are explained in the subsequent sections.

2.2.1 Localisation Technologies

This section describes in detail the various technologies that can be used for localisation.

1. *WiFi:* It is commonly represented as the IEEE 802.11 standard. It has a range of about 100m to 1km (with the latest 802.11ah standard) The ubiquitous nature due to its large scale deployment and its inclusion in all devices such as smart phones, laptops and sensor modules make it a good choice for localisation applications. This technology can employ RSS, CSI, TOF and AOA techniques (or a combination of all of them) to provide WiFi based localisation services.
2. *Bluetooth:* Bluetooth consists of physical and MAC layers to provide communication between devices within a certain space. It has a data transfer rate of about 24 Mbps and coverage range of 70-100m. Bluetooth can be used with localisation techniques such as RSS, AOA, TOF.
3. *Zigbee:* It is a standard that includes physical and MAC layers for low cost, low data and energy efficient personal area networks. Zigbee devices are capable of multi-hop routing. Though it is useful for localisation of wireless sensor units, it is not employed for normal localisation purposes.
4. *RFID:* Radio Frequency Identification (RFID) transmits information using electromagnetic transmitters between compatible RF enabled circuits. RFID tags transmit data that an RFID reader can read using

Table 2.1: Summary of advantages and disadvantages of different localisation technologies

Technology	Advantages	Disadvantages
WiFi	widely available, does not require extra hardware	requires complex processing algorithm, prone to noise
Bluetooth	high range, low energy consumption	prone to noise, low localisation accuracy
RFID	low power, high range	low localisation accuracy
UWB	immune to noise, high localisation accuracy	short range, requires extra hardware
Zigbee	high range, low power	not suitable for range based localisation techniques

a pre-defined protocol known to both reader and tags a priori. The RFID tags are of two types.

(a)*Active RFID:* These operate in ultra high frequency and microwave frequency range. The tag periodically transmit their ID and can operate at 100m from the RFID reader. However, sub meter level tracking accuracy cannot be achieved.

(b)*Passive RFID:* The passive tags works without the use of batteries. They operate and exchange information based on the energy provided by the reader. This limits the range to about 1-2m and thus cannot be used for localisation.

5. *Ultra-wide Band (UWB):* Signals transmitted operate in large bandwidth of (3500 MHz) in a frequency range of 3.1 to 10.6 GHz. Signals transmitted here are of very short duration making them less susceptible to multi-path effects. The larger bandwidth also allows for devices to exchange more accurate time stamps and thus employing the concept of TOF, more accurate ranges can be obtained. UWB provides in the sub meter level accuracy in localisation.

A quick summary of the advantages and disadvantages of the various technologies can be found in the table 2.1

2.2.2 Localisation Techniques

This section describes the various techniques applied on the signals of different technologies to achieve maximum localisation.

1. *RSS:* It is commonly known as the received signal strength. It is the actual signal power (measured in milli-watt) received at the receiver. It is commonly represented as RSSI that has a relative measurement to the RSS depending on the chip manufacturers [11]. The distance of the receiver from the transmitter can be calculated by using the path loss expression shown in the equation 2.1.

$$RSSI = -10n \log_{10}(d) + A \tag{2.1}$$

2. *Channel State Information:* Different frequencies within a signal exhibit different amplitude and phase behaviour. The channel frequency response (employed in this method) captures both the amplitude and phase responses of different signals between separate transmitter receiver antenna pairs given by equation 2.2. Such information is then used by techniques like Orthogonal Frequency Division Multiplexing for more stable measurements and higher localisation accuracy [11].

$$H(f) = |H(f_i)|\, e^{\angle H(f_i)} \tag{2.2}$$

3. *Angle of Arrival:* This method uses antenna arrays at the receiver side to estimate the angle at which transmitted signal is received by exploiting the time difference of arrival at individual elements of the antenna array [11].

4. *Time of Flight:* The time of flight exploits the signal propagation time to calculate the distance between transmitter and receiver. The time of flight is multiplied by the speed of light to get the actual distance. This method requires strict synchronisation in time keeping between the transmitter and the receiver. Assuming that t_1 is the time taken by the i^{th} transmitter to send a message which is received by the j^{th} receiver at time t_2, equations 2.3 and 2.4 give the distance covered by the signal [11].

$$t_2 = t_1 + t_p \tag{2.3}$$

$$D_{ij} = (t_2 - t_1)v \tag{2.4}$$

5. *Time Difference of Arrival:* TDoA relies on finding the relative location of the mobile transmitter based on the time difference of its transmitted signal arriving at different anchor (measuring) points. The transmitter shall lie on the hyperbola with a constant range difference between two measuring points. It is important to note that the anchor points (measuring units) are synchronised by a global clock [11].

6. *Two-way Ranging:* This is similar to time of arrival but alleviates the need for a global clock by sending at least two messages between transmitter and receiver as seen in Fig 2.2 [9]. The propagation time can be calculated from equations 2.5 and 2.6.

$$t_{roundA} = 2t_p + t_{replyB} \tag{2.5}$$

$$t_p = (t_{roundA} - t_{replyB})/2 \tag{2.6}$$

The advantages and disadvantages of different localisation techniques have been summarised in table 2.2.

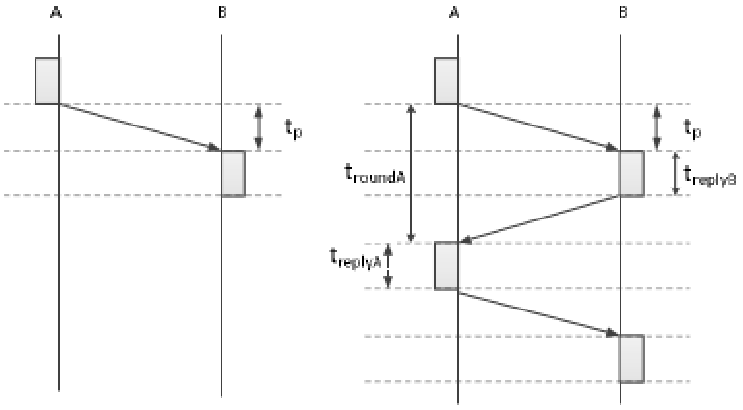


Figure 2.2: Time of Arrival (left) vs Two Way Ranging (right) [9]

Table 2.2: Summary of advantages and disadvantages of different localisation techniques

Technique	Advantages	Disadvantages
RSSI	easy to implement, cost effective, can be used with number of technologies	prone to multi-path fading and environmental noise, lower location accuracy
CSI	high localisation accuracy, does not require fingerprinting	not easily available in commercial off shelf hardware
AoA	provides high localisation accuracy	requires directional antennas, complex hardware and algorithms, accuracy deteriorates over larger distances
ToF	high localisation accuracy	requires time synchronisation between transmitter and receivers, might require additional time stamps, line of sight is necessary for maximum accuracy
TDoA	does not require fingerprinting, can provide high accuracy if difference in time stamps is very fine	requires clock synchronisation among receiving points (base stations)
TWR	does not require clock synchronisation among devices, can provide high localisation accuracy	needs additional messages to be transmitted resulting in more power consumption

2.2.3 Selecting appropriate technology and technique

Based on the comparison table 2.1, UWB proves to suit our application better than the other technologies. This is because UWB signals are immune to the multi-path effects which makes it area agnostic and offers centimetre level accuracy. The short ranges of UWB can be overcome by adding extra base stations around the field.

To effectively exploit the unique characteristics of UWB signal which is larger bandwidth, time based localisation techniques (like TOA) are more commonly used. For single path channel, the noise can be modelled as AWGN (Additive White Gaussian Noise), the distance estimate can be expressed as

$$\sqrt{Var(\widehat{d})} \geq \frac{c}{2\sqrt{2\Pi}\sqrt{SNR}\beta} \tag{2.7}$$

where SNR is the signal-noise ratio and β is the bandwidth.
Due to the large bandwidth, the variation in distance estimate would be a

minimum. This shows that UWB systems can achieve higher localisation accuracy.

2.3 Ultra-wide band related work

This section presents previous works in which UWB technology was employed for sporting applications.

Lorenzo et al [15] proposed an ultra wide band real time location system to track player positions and monitor his/her performance during recovery time after surgery. The system employs a hybrid AOA/TDOA ranging technique to track player positions. However, their tests on an outdoor football field (35 m x 40 m) yielded poor localisation results due to bad signal quality on the transceivers. It also resulted in a sub optional sample rate of 2Hz.

Matteo et al [12] experimentally evaluated ultra wide band for indoor sports. This included evaluating the impact of device placement on the body w.r.t to packet loss. It was found that placing the device atop the head yielded the lowest packet loss. This work also implemented two localisation algorithms (particle and Kalman filters) and reports average localisation errors of 20 cm. However, their test on device placement on body did not account for different device orientation and their algorithms were tested indoors.

2.4 Ball Detection

In order to call for off-sides, we need to know which player is in possession of the ball. Since there are no sensors present inside the ball, we would have to identify players who are in close proximity to it. Proximity sensors work on different principles such as magnetic inductance, optical (infrared) sensor and ultrasound. Further details about the use of these proximity sensors w.r.t our application have been discussed in Chapter 5.

Chapter 3

Overview

As discussed in the previous chapter, for calling off-sides we need to know (a) the position of a player on the football field and (b) what he/she was doing at that instant of time (if he/she was actively involved in the play).

We have seen that *Ultra-Wide Band* performs the best for localisation. A proximity based sensor such as a Time of Flight sensor helps us identify which player has the ball.

A custom sporting platform that can be worn by the players to localise and detect player activities was created. This chapter provides an overview of the sport platform designed.

3.1 Requirements

Before describing the sporting platform, it would be worth mentioning the requirements along with their reasoning upon which the system was built. These are described below.

1. The system must be wearable and must easily be worn around the shin.

   Rationale: This is because wearable sensors can easily be integrated into the shin guard. This would prove to be less intrusive to a player.

2. The Ultra-wide Band localisation must be able to give a position estimate every 0.1 seconds (10 Hz) and must have a sub-meter level accuracy.

   Rationale: According to [2], most professional footballers on average sprint to a maximum speed of 9.7 m/s for very short periods of time and run at 6.5m/s otherwise. Thus, localisation of a player 10 times in a second seems sufficient. The localisation must have sub-meter level of accuracy as offside positions have a small relative distance between players.

3. The proximity based sensor must have a sample rate of 10 Hz.

   Rationale: The sample rate of the localisation system and the ball detection system must be the same.

4. The unit must have a large battery to provide 100 minutes of continuous use.

   Rationale: A football match normally lasts about 90 minutes of game time with about 10 minutes of extra added time.

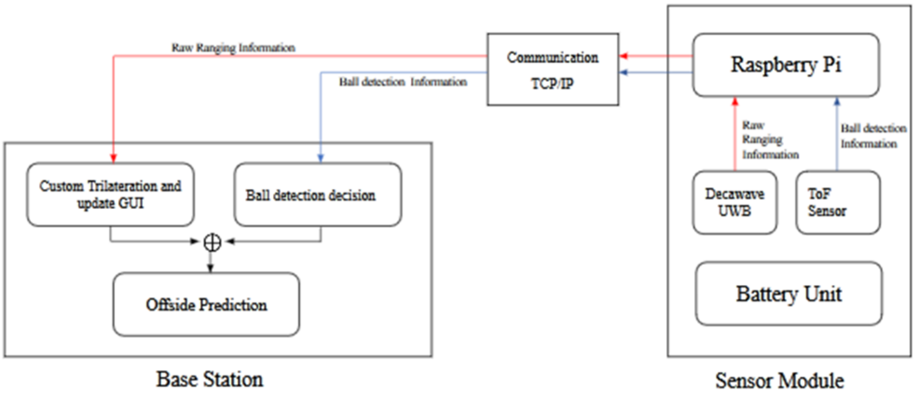


Figure 3.1: **System Overview.** The system consists of a base station and sensor modules that communicate via TCP through Wi-Fi.

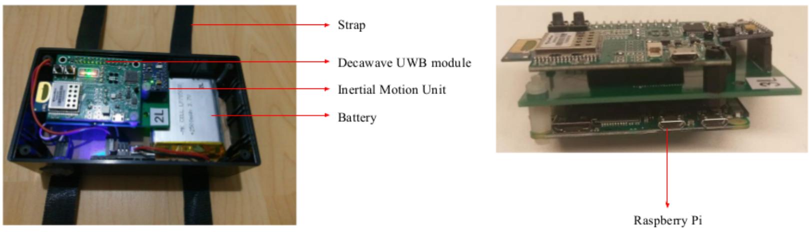
3.2 System Overview

This section describes the main components of the system. It consists of three basic components (a) sensor module, (b) communication and (c) base station. The interaction between various components and their sub-components can be seen from Fig 3.1.

3.2.1 Sensor Module

It is the actual device that is worn by the player around his/her shin. Fig 3.2 shows an implementation of the sensor module. A brief description of the various components of the sensor module are described below.

1. *Raspberry Pi Zero - W:* It is a small computer with a 1 GHz processor and 512 MB of RAM running Linux OS which provides flexibility for developing applications. It also has an on-board Wi-Fi and SD card logging unit. The module also supports bash scripting, this makes it very easy to automate the start-up procedures of the sensor module (i.e passing commands to the UWB module to get the ranging information).
2. *Decawave DWM 1001:* It is the part which handles the localisation of a player. The chip is essentially an Ultra-wide band radio module. It is interfaced to the Raspberry Pi via UART. The output is a string of data with ranging information of a tag to the various anchor points placed around the field.
3. *Time of Flight sensor:* The Time of Flight sensor is used for sensing which player is in possession of the ball. More information on its working can be found in chapter 5.
4. *Battery unit:* The battery chosen to power this module was a lithium ion cell. This is because of it's high energy density. The battery has a capacity of 2500 mah at 3.7 V. Since the Raspberry Pi runs at 5 V, a DC-DC boost converter was incorporated to boost the voltage 5 V at 1 A.



(a) Top view of the sensor module.

(b) Side view of the sensor module.

Figure 3.2: Prototype implementation of the sensor module.

3.2.2 Communication

The communication of data from the sensor module can be streamed to the base station in real time or can be stored locally on the SD card of the Raspberry Pi and be processed later. In case of real time needs, the data is streamed to the PC via Wi-Fi using the TCP Internet protocol. The TCP provides reliable, ordered and error checked delivery of bytes from node to base station.

3.2.3 Base station

It is a PC that acts as a server and accumulates data from all the sensor modules deployed. The main functions of the base station are

- Acquire data from all sensor modules.
- Running custom tri-lateration algorithm method for localisation and display on the GUI.
- Acquire the data from the ToF sensors.
- Combine the information from both sensors and make an informed decision.

Chapter 4

Localisation

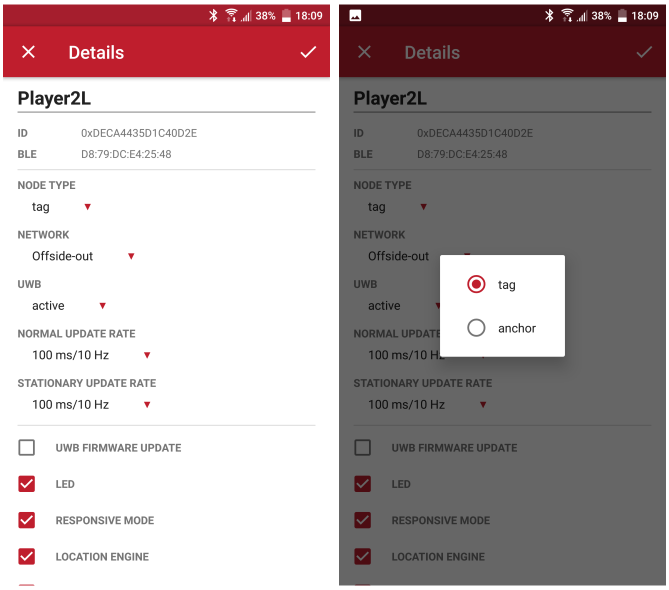
The main functionality of the Ultra Wide Band module is to localise players on the football field. From chapter 2, we have seen why UWB performs better in localisation when compared to other RF technologies. We have also elucidated why Two Way Ranging method was used as the technique to obtain range estimates from the base station. This chapter presents an evaluation of the performance of the system with regards to our application and subsequently make improvements on the same.

4.1 Decawave Ultra-wide Band Device

The Decawave UWB device is based on the IEEE 802.15.4.201 standard. It has a central frequency of 6.5 Ghz and 6.8 Mbps frame data encoding. The device localises itself by exchanging time stamps. The sections below explain the communication protocol of the device.

4.1.1 Device Configuration

The Decawave DWM 1001 device is homogeneous in nature. Thus, the same device can be used either as a node (devices worn by players), anchor point (base stations on the sides of the field) or as a listener (a device that reports the position information of all the nodes). The configuration of devices can be done by using the accompanying Android application provided by Decawave as seen in Fig 4.1. The app takes the user input and sends the appropriate commands to the devices via Bluetooth.



Player2L

ID 0xDECA4435D1C40D2E

BLE D8:79:DC:E4:25:48

NODE TYPE: tag

NETWORK: Offside-out

UWB: active

NORMAL UPDATE RATE: 100 ms/10 Hz

STATIONARY UPDATE RATE: 100 ms/10 Hz

☐ UWB FIRMWARE UPDATE

☑ LED

☑ RESPONSIVE MODE

☑ LOCATION ENGINE

● tag

○ anchor

(a) Configuration menu of device (b) Selection between anchor or tag configuration

Figure 4.1: Configuration of a device via the Decawave Application

4.1.2 Network Formation

The UWB device forms a network comprising of anchors and nodes. Devices in the network utilise the TDMA channel access. Localisation is achieved by passing messages between anchors and nodes. These messages contain time stamp information which is used by the nodes to calculate different ranges with the anchors through a method called Two-way ranging (discussed in chapter 2). A typical message structure (super frame message) is shown in Fig 4.2. The operation of anchors and nodes in an UWB system is described as follows.

1. Every network has an initiator which controls the timing of super frame messages.

2. Every message is 100 ms in duration. It contains 16 Beacon message slots, 2 Service slots and 15 Two-way ranging slots

3. The initiator anchor starts the network discovery by transmitting the super frame message. The other anchors in the network on start up listen for beacon messages and try to join the network. Upon joining the network, they will be assigned a beacon slot and start sending messages containing their own coordinates on the field and general information of the network.

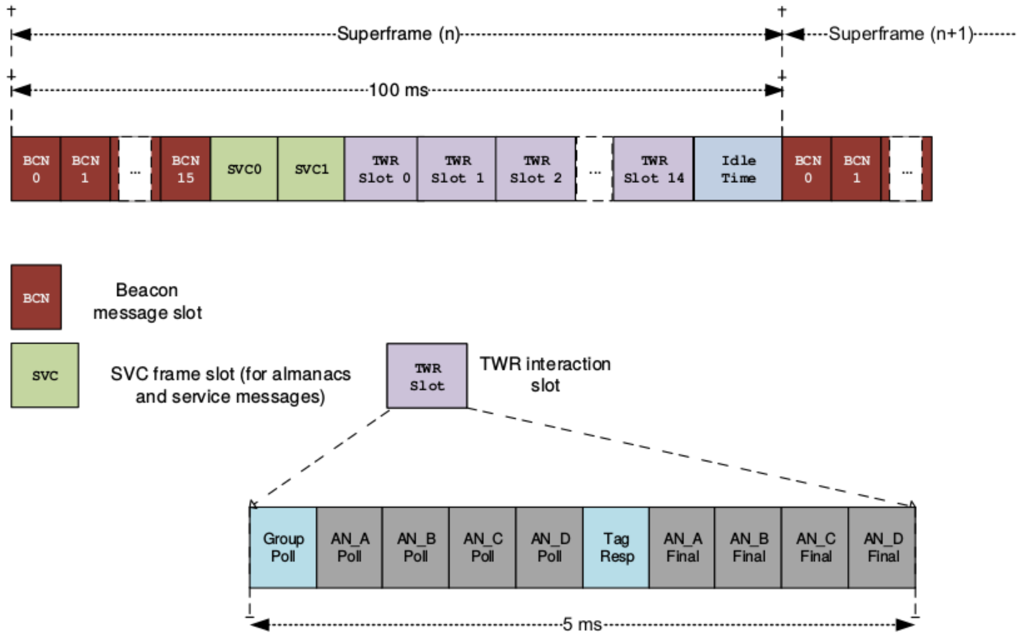


Figure 4.2: Communication protocol of devices in network [1]

4. The total number of anchors that can operate in an area is 16 (limited by the number of Beacon slots).

5. A tag in the network listens for Beacon messages. While establishing compatibility of firmware, it tries to reserve a TWR slot. A super frame can range up to 15 tags simultaneously. If no slots are available, the tag waits for a period and tries again. Each slot lasts for about 5 ms as shown in Fig 4.2. Within slots the node communicates with the anchor via the TWR techniques. The following steps take place

   - The tag sends a group poll (broadcast) message containing its TWR slot information to the anchors it wishes to range.

   - The listed anchors listed will respond with a poll message back to the tag. The tag sends another response message and it is followed by a final message from the anchors. These messages contain the time stamp information and the tag uses the difference in these time stamps to calculate ranges.

4.2 Localisation Challenges

A primary evaluation of the stock solution (i.e using the UWB modules with stock software) proved to be unsatisfactory for our application. From figure 4.3 we see that for a player moving along a certain path (marked by the black line) on a field surrounded by anchor points (base stations - represented by grey dots) on its sides, there is a lot error in reported positioning information. The maximum error in localisation accuracy is about 6 m and the overall root mean square error in accuracy for the entire path is about 73 cm. We also see that a number of points with high magnitudes of error (about 4 m) are being reported. The system also suffers from packet loss of about 27 %.

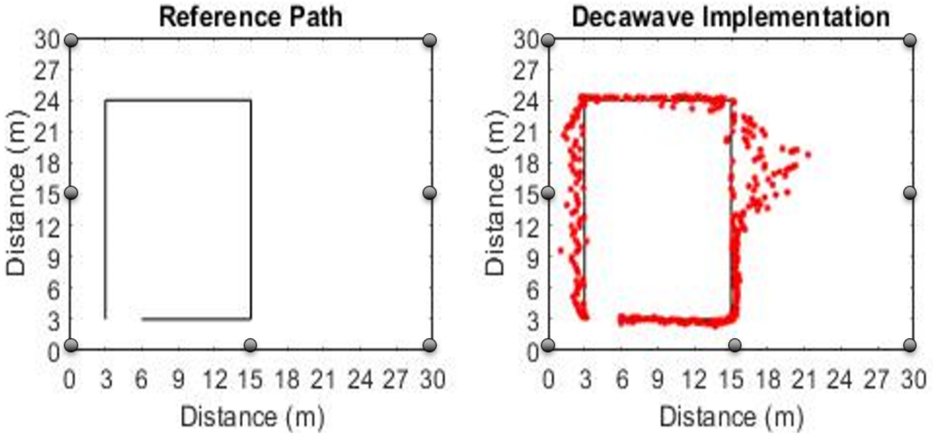


Figure 4.3: Stock Localisation solution for a player moving on the football field

Thus, the challenges that plague the current localisation system are

- Packet loss
- Lack of time stamp information conveyed
- Accuracy errors

In the subsequent sections, we will identify the root causes of these challenges and propose new methods to rectify them.

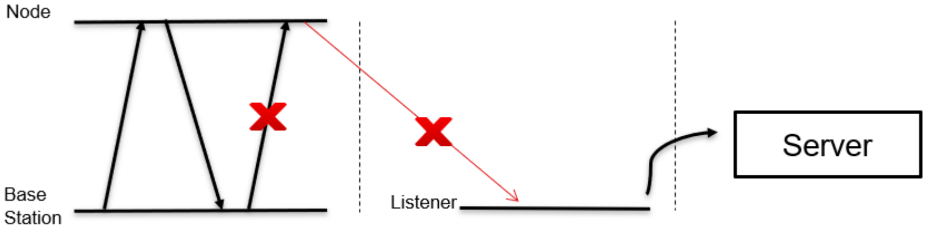
4.3 Packet Loss and Time-stamping

The packet reception of the UWB device plays a significant role in our application. Problems with packet reception would mean not being able to sample the location of a player at 10 Hz. Packet reception depends upon

Table 4.1: Packet reception for nodes mounted at different heights

Position of Tags (cm)	Average Packet Reception Rate
40	93.12 %
100	85.37 %
150	92 %

where the UWB sensor is mounted on the player and natural losses. Packet losses in the UWB system can be because of (a) failure of the node to range with the anchor points (Packet Loss - Estimation) or (b) failure of the listener device to capture the reported positioning information from the node (Packet Loss - Reporting). Figure 4.4 shows packet loss due to different scenarios. The overall packet loss in the worst case scenario is the sum of packet losses due to estimation and reporting. The information communicated with the server is also not time stamped which is critical to our application.



Packet Loss : Estimation	Packet Loss : Reporting	Packet Loss : Overall
26.94	9.4	35.8

Figure 4.4: Packet Loss for different Scenarios

4.3.1 Packet Reception - Where to put the sensor?

Packet reception is heavily dependent on where the UWB sensor is mounted on the player. An experiment to identify the key area on which the sensor should be mounted was performed. This experiment involved mounting different nodes on a metallic tripod at different heights as show in fig 4.5. This setup was then placed in an area surrounded by UWB base stations that were suspended 2 m above the ground. From table 4.1 we find that the sensor mounted lower to the ground gives us a better packet reception rate. This is because of the better line of sight between the node and anchor.

Thus, we found it would be ideal to mount the sensor around the shin area of the player's leg. Another advantage of mounting the sensor at this

Figure 4.5: Nodes mounted at different heights on a metallic tripod (right) in a predetermined field setup (left)

position is that it can be easily integrated into the shin guard and prove to be less intrusive for the player. The prototype as discussed in chapter 3, was designed based on this reasoning.

It was also found that the orientation of the device on the player's body also contributed to the packet reception rate. This is because human bodies are capable of absorbing the UWB signal. By shifting the orientation of the device to the side of the leg as seen in fig 4.6 (b), we find that the packet reception rate increases from 77.3 % to 96.7 %.

(a) Device on the front

(b) Device on the side

Figure 4.6: Placement of node devices on player's leg

4.3.2 Packet Loss - Reporting

One of the reasons of packet loss in the UWB sytem is because the node failed to communicate its estimated position to a listener device in the UWB network. This is chiefly because of Non Line of Sight between the node on the player and the listener device.

Our prototype proposes a work around to this challenge by logging all the data locally on the Raspberry Pi's SD card and then sending the data via TCP through WiFi. This ensures a more robust method of reporting position estimates.

4.3.3 Packet Loss - Estimation & Time stamping

Packet losses occur primarily because the node is unable to range with a base station due to the lack of Line of Sight between the two devices. In order for the node to report a position estimate, it needs to range with at least 3 base stations. Each range comprises of a series of messages passed between the node and the base station it wants to estimate its distance from. This means that a failure due to Line of Sight of even a single message during the ranging phase would result in the range not being reported. Thus, the node in this case would have distance estimates from less than 3 base stations making it impossible for the node to use tri-lateration and report a position estimate.

To alleviate this problem, our prototype was designed to share raw ranging information amongst the nodes mounted on the player's shins. Since, our prototype was designed on the Raspberry Pi platform, the data communicated by the UWB device can be time stamped locally. The time stamps across all the nodes in the field would be synchronised as all nodes communicate to the same server and the Linux kernel ensures this functionality. The time stamped raw ranging information from both shin guards worn by a player are transmitted to a central base station (fig 4.7). The central base station can combine the required ranging information and then tri-laterate the player's position.

4.4 Improving Localisation Accuracy

In this section we aim to improve the localisation of the UWB system. The main source of errors observed were due to errors in distance estimates during ranging process of the node and placement of the anchor points on the field. In the subsequent subsections, we about the errors in detail and propose solutions to overcome them.

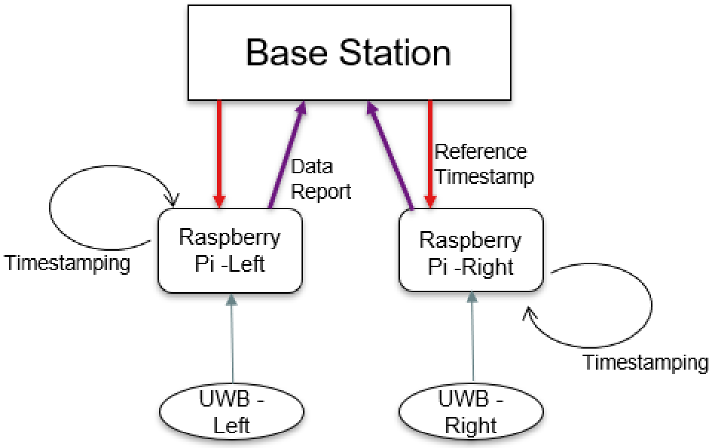


Figure 4.7: Sharing and Time stamping mechanism

4.4.1 Errors due to Ranging

We aim to seek the maximum possible distance at which the UWB can perform with reasonable accuracy. The experiment involves mounting an anchor point on a stand 2 m high. The tag was taken 10 m, 20 m and 30 m apart. Successive iterations where taken and the median, max and min values are seen from the box plot below (refer to fig 4.8). From, the figure we can see that for distances between 10-15 m the ranges reported has an error in the sub-meter level. For, 20 m and above the error in ranging increases to 1 m. Thus, for this application we limit the maximum range from each anchor to 15 m and design our field setup accordingly.

4.4.2 Field Setup

Going by our previous experiment, we design a field of 30 m x 30 m to emulate half of a normal football field. This setup is sufficient as off-sides normally occur on one half of the field. Also, the measurements acquired may be symmetric across the field. Fig 4.9 shows the field setup. Anchor points are placed evenly 15 m apart on the sides of the field so as to not introduce errors in the ranging process. An offset of 1 m in the placement of the central anchor point was introduced to reduce the effect of co-linearity in tri-lateration.

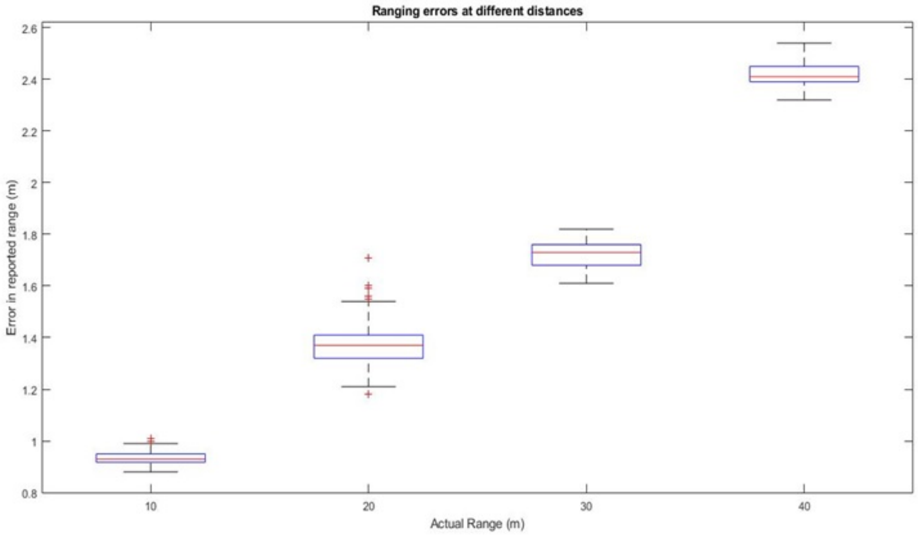


Figure 4.8: Ranging accuracy of a node at 10, 20, 30 and 40 m from anchor

4.4.3 Errors due to Tri-lateration algorithm

As previously stated, the errors in localisation can go as high as 6 m. The position reporting algorithm (tri-lateration algorithm) on the Decawave device is proprietary and very few details are available. From the product documentation we understand that the tri-lateration is based on the Maximum Likelihood Estimation (MLE) approach. Implementation of the MLE algorithm for position estimation on micro-controller based devices reduces to the Linear Least Square Method. Based on this hypothesis, a reverse engineered tri-lateration algorithm was developed which is described in the

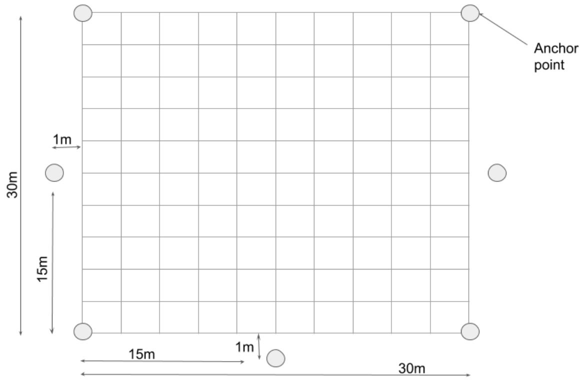


Figure 4.9: Field setup

following paragraphs.

The equations for the estimated ranges can be expressed by equation 4.1 where x_i, y_i (for i=1,2..n) are the x and y co-ordinates of the anchor points.

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2 \tag{4.1}$$

The above equations are quadratic in nature and to convert them into a linear form we add and subtract x_j and y_j, where j here can be a reference anchor to which other ranges are compared [10].

$$(x - x_j + x_j - x_i)^2 + (y - y_j + y_j - y_i)^2 = r_i^2 \tag{4.2}$$

with (i=1,2,...,j-1, j+1,...n)

By expanding and regrouping 4.2 we arrive at

$$\begin{aligned} (x - x_j)(x_j - x_i) + (y - y_j)(y_j - y_i) \\ = 0.5[(x - x_j)^2 + (y - y_j)^2 + -r_i^2 + (x_i - x_j)^2 + (y_i - y_j)^2] \\ = 0.5[r_j^2 - r_i^2 + d_{ij}^2] = b_{ij} \end{aligned} \tag{4.3}$$

where

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{4.4}$$

is the distance between anchors B_i and B_j.

The equation 4.3 can be re-written in a matrix form as

$$A\overrightarrow{x} = \overrightarrow{b} \tag{4.5}$$

with

$$A = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix}, \qquad \overrightarrow{x} = \begin{bmatrix} x - x_1 \\ y - y_1 \end{bmatrix}, \qquad \overrightarrow{b} = \begin{bmatrix} b_{21} \\ b_{31} \end{bmatrix} \tag{4.6}$$

Since the ranging information is approximate, an approximation of equation 4.5 based on minimising the sum of squares of the residuals leads to the equation below.

$$A^T A\overrightarrow{x} = A^T\overrightarrow{b} \tag{4.7}$$

Provided $A^T A$ is non-singular, the position estimate can be found by the equation 4.8

$$\overrightarrow{x} = (A^T A)^{-1} A^T\overrightarrow{b} \tag{4.8}$$

A comparison between the stock Decawave's tri-lateration algorithm and our reverse engineered algorithm can be seen from Fig 4.11. We see that though the position estimates from both the algorithms are not exactly the same, the figures share similar overall error characteristics. Due to internal optimisation, the Decawave algorithm certainly out performs our reverse engineered hypothesis. However, the similarity in the error characteristics indicates that the error in localisation accuracy is because of a failure in the tri-lateration algorithm.

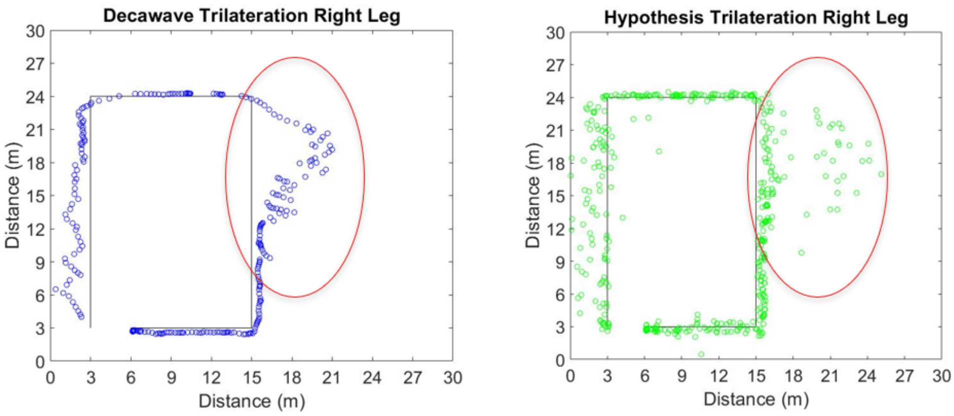


Figure 4.10: Decawave vs Hypothesis Algorithm

Error Analysis in Tri-lateration

In fig 4.11 we we provide a detailed analysis of the estimation process. The figure shows the anchors used to estimate the location for each point. We can see that most of the location estimates marked in green have their ranging estimates from the 3 base stations on the same side of the field. The base stations here although not placed in a straight line are placed in an almost collinear fashion. The error in the reported position is because of the failing in the Linear Least Square Algorithm. Particularly, the problem lies with the linear transformation in this algorithm. On further expansion of equation 4.6 we get

$$(x_2 - x_1)(x - x_1) + (y_2 - y_1)(y - y_1) - b_{21} = \xi_1 \tag{4.9}$$

$$(x_3 - x_1)(x - x_1) + (y_3 - y_1)(y - y_1) - b_{31} = \xi_2 \tag{4.10}$$

Since equation 4.6 was an approximate equality, two terms ξ_1 and ξ_2 are introduced as accumulation of error constants.

Let us consider two cases of ranges reported by the nodes of the location system. In one case, the ranges are from non collinear anchor points as seen

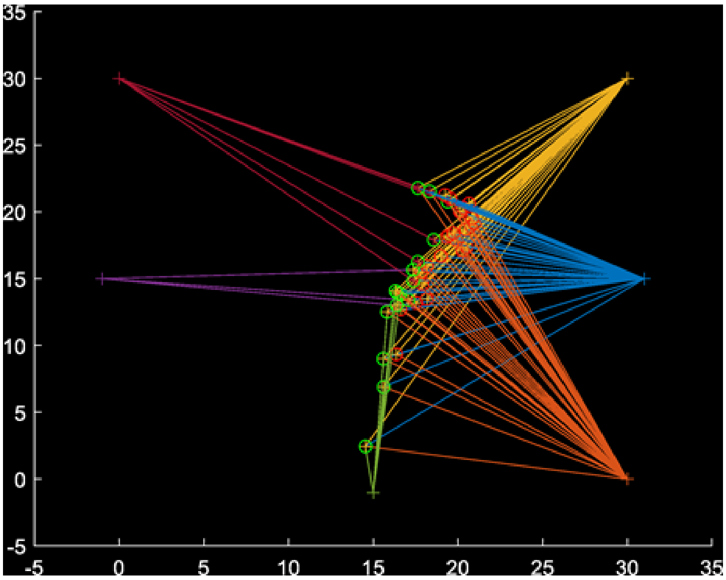


Figure 4.11: Tracing ranging base stations for erroneous position estimates

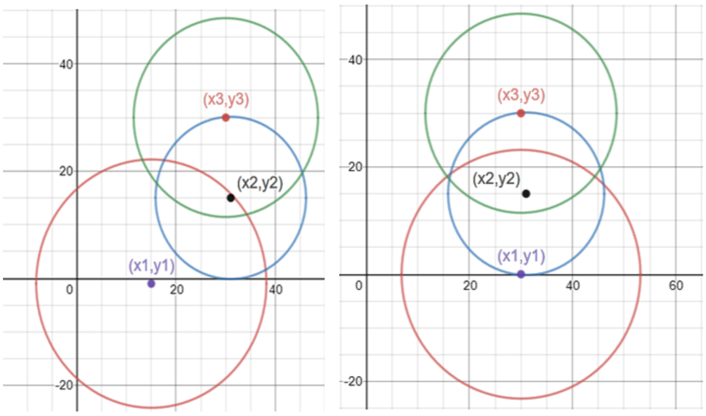
in fig 4.12 (a) and in the other case the ranges are from almost collinear base stations as in fig 4.12 (b).

In both cases, converting the quadratic forms of the ranging equations to a linear form involve representing all the ranges with respect to a common anchor point (in this case it is an anchor with coordinates x_1 and y_1). The solution to these equations are the position estimates represented by x and y.

The differences between the coordinate points of anchors and error terms in equations 4.9 and 4.10 are predetermined and cannot be varied. Since our objective is to minimise the error constants, we have to vary our unknown variables x and y, such that it's difference with the reference coordinates x_1 and y_1 are a minimum.

This means that when the anchor points are not in a collinear fashion as in fig 4.12 (a), the difference between the coordinate points of the anchors will be sufficiently large. It implies that the difference between our unknown parameters and the reference coordinates ($(x - x_1)$ and $(y - y_1)$) would be small.

However, when the anchors are placed in a collinear fashion as in fig 4.12 (b), the difference between the coordinate points of the anchors will be small. This means that, the difference between our unknown parameters and the reference coordinates ($(x - x_1)$ and $(y - y_1)$) would be very large and would introduce errors in the estimated position.



(a) Ranges from Non-collinear anchor points (b) Ranges from collinear anchor points

Figure 4.12: Placement of anchor points

Solution

To alleviate the above problem we use the Non Linear Least square approach. This method does not convert the ranging equations to a linear form and uses numerical methods to estimate the solution. The following paragraphs describe the solution.

The ranging information have sources of error and we need to minimise the sum of the squares of the distances. This is achieved by minimising the equation 4.11

$$F(x,y) = \sum_{i=1}^{n} f_i(x,y)^2 \tag{4.11}$$

where

$$f_i(x,y) = \widehat{r}_i - r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} - r_i \tag{4.12}$$

In equation 4.12, x_i, y_i, r_i represent the x,y co-ordinates and ranging information of an anchor point B_i. Here x and y represent the initial estimation of the player which can be calculated by using 4.8. The Newton iteration method was chosen to find the optimal solution from the minimisation problem stated above. As, it is a minimisation problem, $F_{min} > 0$. Differentiating with respect to the x-axis we get

$$\frac{\partial F}{\partial x} = 2\sum_{i=1}^{n} f_i \frac{\partial f_i}{\partial x} \tag{4.13}$$

The formula for the partial derivative with respect to y is similar to equation above. The Newton iteration formula gives rise to equation 4.14

$$\overrightarrow{R}_{k+1} = \overrightarrow{R}_k - (J_k^T J_k)^{-1} J_k^T \overrightarrow{f}_k \tag{4.14}$$

where

$$J^T J = \begin{bmatrix} \sum_{i=1}^n \frac{(x-x_i)^2}{(f_i+r_i)^2} & \sum_{i=1}^n \frac{(x-x_i)(y-y_i)}{(f_i+r_i)^2} \\ \sum_{i=1}^n \frac{(x-x_i)(y-y_i)}{(f_i+r_i)^2} & \sum_{i=1}^n \frac{(y-y_i)^2}{(f_i+r_i)^2} \end{bmatrix}, \tag{4.15}$$

$$J^T \overrightarrow{f} = \begin{bmatrix} \sum_{i=1}^n \frac{(x-x_i)f_i}{(f_i+r_i)} \\ \sum_{i=1}^n \frac{(y-y_i)f_i}{(f_i+r_i)} \end{bmatrix}, \overrightarrow{R} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{4.16}$$

Here, vector $\overrightarrow{R}_k$ represents the $_kth$ approximate solution. An optimal solution is obtained once $\overrightarrow{R}_{k+1}$ is equal to $\overrightarrow{R}_k$.

This method can be visualised graphically using contour plots. For ranges originating from the collinear base stations, the contour plot as seen in fig 4.13 shows that there are two local minimum. However, we can eliminate one solution as it clearly lies outside the football field dimensions.

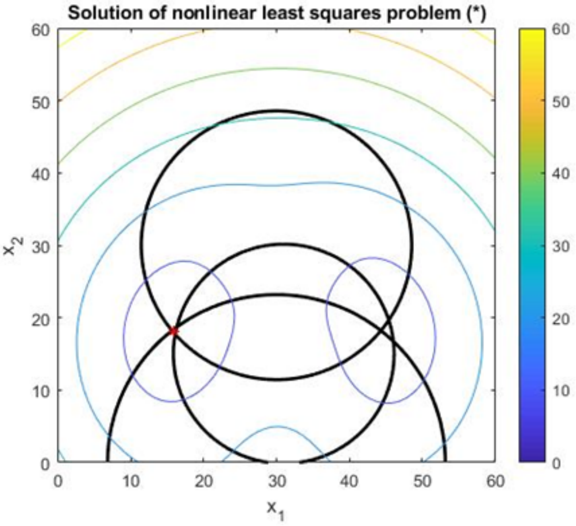


Figure 4.13: Local Mimima estimate

Fig 4.14 shows our iterative method keeps converging to a local minimum, given that we start from an erroneous position estimate from the Least Square algorithm.

The drawback of this solution is that it is computationally more expensive than the Linear Least square method. However, in our application the server base station runs this routine and has enough computation power to handle the processing demands.

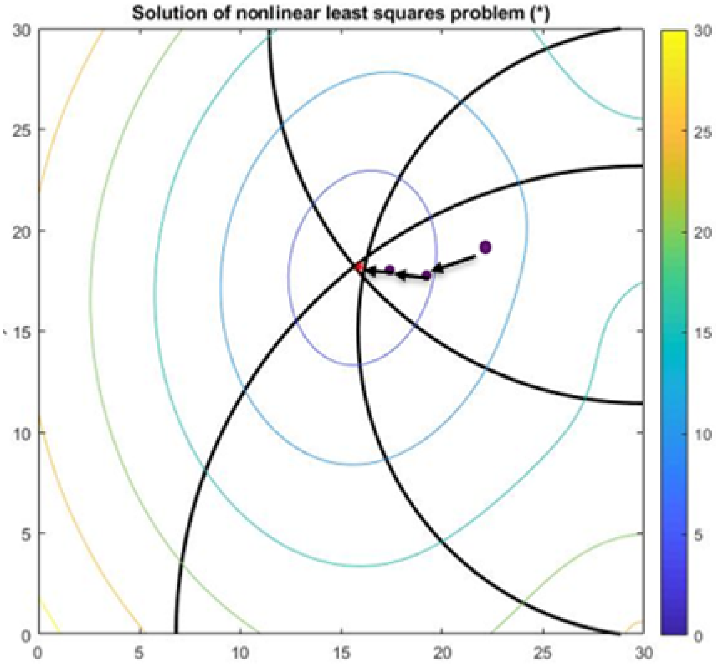


Figure 4.14: Converging to local minima using iterative method

Chapter 5

Ball Detection

5.1 Overview

Through the previous chapter, we have achieved high levels of accuracy in the localisation. However as mentioned in Chapter 2, an offside is only called if the players of an opponent team are in an offside position and if they are actively involved in the play.

This condition can be viewed as a proximity problem. That is, we would have to identify which players are in close proximity (possession) to the ball. Here we propose to use sensors attached to the shin guard of the players to identify ball possession. There are various proximity sensors that use different principles. From Chapter 3, our requirements need a sensor that is easily portable, has a good sampling rate and detect objects in sight up to 30 cm.

Different approaches have been tried in this thesis to meet all of our prefixed requirements and have been met with varying levels of success. These approaches are discussed in detail in the subsequent sections.

5.2 Approaches towards Ball Detection

5.2.1 Inductance Based Approach

The principle of electromagnetic induction can be used to detect objects. For our application, a metal detector circuit as seen in fig 5.1 was developed.

The circuit changes its oscillation frequencies based on the change in inductance of the coil. In order to make the ball behave as a metallic object,

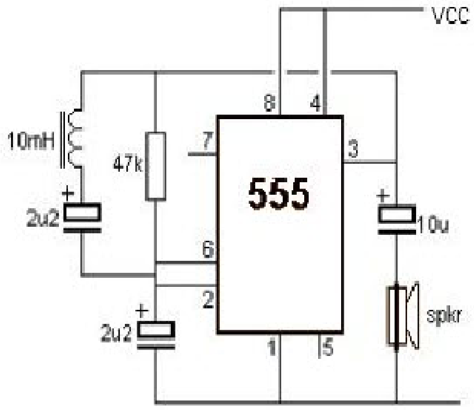


Figure 5.1: Metal Detector circuit using 555 timer

strips of aluminium foil were stuck on the surface of the ball. The foil pieces do not add any significant weight nor change the aero dynamic properties of the ball. However, this proximity method proved to be a failure as the inductor coil would have to be large in size in order to detect a metallic object at a distance of 50 cm. This method proved to be in-feasible as there is no space on the shin guard for a large inductor coil and this will result in adding extra weight on the players.

5.2.2 Magnetic Based Approach

Magnetometer sensors measure the magnetic flux density. To employ this principle in our application, magnetic strips were stuck on the ball and a magnetometer was integrated with our sport platform.

However, the magnetic strips add additional weight to the ball and also change the aerodynamic properties due to the thickness of the strips. It was also found further that the detection of the ball (with strips) greatly depends upon the position w.r.t the ball.

5.2.3 Ultrasound sensor

The ultrasound sensor is a proximity based sensor that employs the reflection of sound waves in order to estimate the distance from an object. It is simple in construction and can detect objects up to 4 m. With regards to our application, this sensor did not perform very well as we could not control the field of view and the measurements were very noisy as the player started to move.

5.2.4 Time of Flight Sensor

The Time of Flight sensor contains a very tiny laser source and a matching sensor. It measures how long the laser light has taken to bounce back to the sensor. Since it uses a very narrow light source, it is good for determining distance to surfaces directly in front of it. In this case the signal emitted is a short pulse of laser light. The sensor can range up to 4 m and has a sampling rate of 50 Hz. Unlike IR distance sensors that try to measure the amount of light bounced, the ToF sensor is much more precise and doesn't have linearity problems or 'double imaging' where you can't tell if an object is very far or very close. For it's accurate and robust ranging capabilities, this sensor fitted our requirements to the best.

Chapter 6

Evaluation and Results

This chapter presents the results and evaluation of the developed system. Section 6.1 presents the experiments that evaluate the existing UWB system and compares Decawave's tri-lateration algorithm with our own custom algorithm.

6.1 Localisation Accuracy

As discussed in chapters 4, the main problem with the UWB localisation system was due to placement of base stations in a nearly collinear fashion resulting in large localisation errors.

6.1.1 Setup and Procedure:

In this experiment, the players wore the custom prototypes around their shins. Each player was asked to move along a predefined path on the field. The data collected from the UWB module was logged on the internal SD card of the Raspberry Pi. The commands to start/stop logging on these devices are sent from an external base station through WiFi. The results reported are the average position from each shin guard worn by the player.

6.1.2 Results

Taking a single trial (a player travelling on a path) we can see from Fig 6.1 that our custom tri-lateration method performs better than Decawave's implementation.

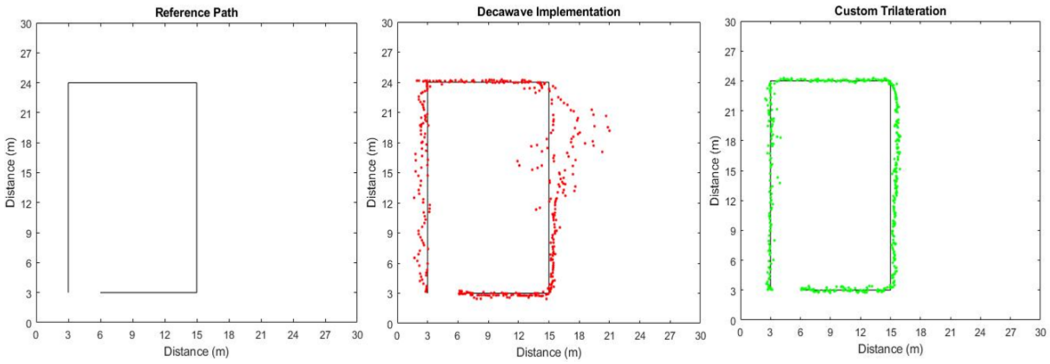


Figure 6.1: Decawave vs. Custom trilateration method

The overall comparison of RMSE of localisation accuracy for all trials can be seen from Fig 6.2. We find that our custom tri-lateration method is on average 56% better than the Decawave implementation.

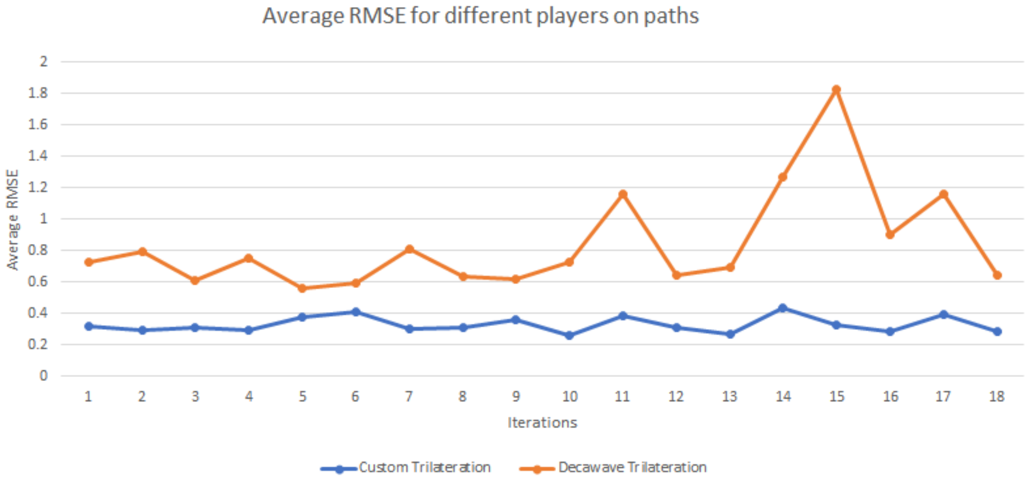


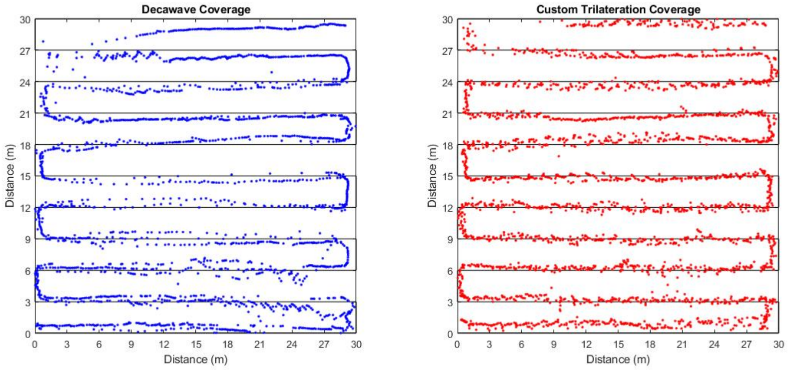
Figure 6.2: Decawave vs. Custom tri-lateration method

6.2 Coverage

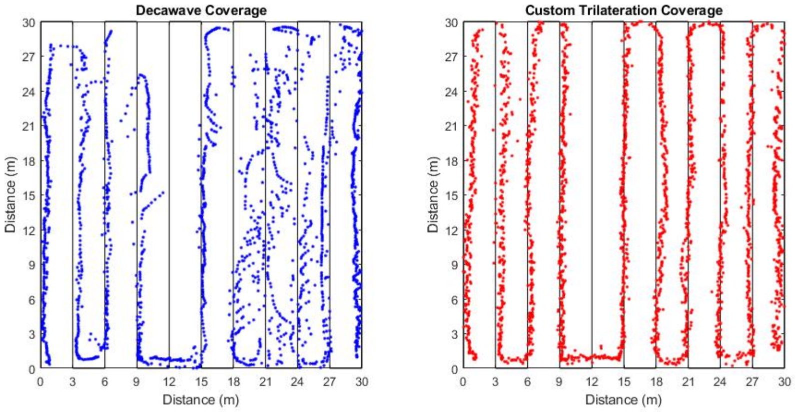
Another problem faced by the localisation system is packet loss. In this section we evaluate the packet reception of our custom tri-lateration method vs. Decawave's implementation.

6.2.1 Setup and Procedure

The setup is similar to that of 6.1.1 except that this time player moves along all the grid lines in both horizontal and vertical directions to cover the entire field.



(a) Comparison of accuracy amongst Decawave's vs custom firmware along horizontal paths



(b) Comparison of accuracy amongst Decawave's vs custom firmware along vertical paths

Figure 6.3: Coverage analysis of Decawave's vs custom firmware for paths on football field

6.2.2 Results

Figure 6.3 shows the comparison of Decawave's vs custom firmware for the above cases. The packet reception rate of the player moving along the horizontal line of the field increased from 52.90 % to 94.98 %. For the player moving along the vertical lines the packet reception rate improved from 43.56 % to 92.99 %.

6.3 Offside Evaluation

Through the previous section, we have determined that our custom localisation solution performs better. We thus, use this method to further evaluate the system w.r.t. our application.

6.3.1 Setup and Procedure

In this experiment, we seek to evaluate the performance of the localisation system in an actual offside scenario. The setup involved having two players stand at a predetermined distance apart at various parts of the football field.

Table 6.1: Offside Evaluation

Distance Apart (m)	Offside	Not Offside
2	96.4427	3.5573
1	96.1918	3.8082
0.50	94.8929	5.1071
0.30	93.253	6.747
0	47.4453	52.5547

6.3.2 Results

At various distances between the two players, the number of offside calls is recorded in Table 6.1. We find that as the relative distance between the players decreases the ability to detect an offside also reduces. When two players are at a zero relative distance, the chances of detecting an offside is 50% because the players are standing on the same line.

6.4 Ball Detection

From the previous chapter, we concluded that the Time of Flight sensor performs best for our application.

6.4.1 Setup and Procedure

For this experiment, the ToF sensor was mounted on front side of the shin as shown in the figure 6.4. A ball was passed to the player a number of times. The information from the ToF sensor was logged on the SD card of the Raspberry Pi. If the sensor gave a range reading of less than 30cm, the player was considered to be in possession of the ball.

Figure 6.4: Mounting of ToF sensor on leg

6.4.2 Results

The results recorded show that out of 43 kicks that were played, the sensor reported 44 kicks. The results are in bound with the requirement of our application.

Chapter 7

Conclusions and Future Scope

7.1 Conclusions

Through the completion of this thesis, a sensor based system that can identify off-sides in a football game has been realised. The major contributions of the thesis has been identifying the appropriate technologies for localisation, developing an expandable sport platform and evaluating different methods to detect the presence of a ball near the player, (which was modelled as a proximity problem). A number of challenges were overcome during the completion of this thesis.

Firstly, the UWB localisation system which was evaluated did not meet our requirements. Particularly the localisation accuracy was not within the bounds of 50 cm of error. Through investigations we found that the tri-lateration method employed by the UWB system fails when collinearity is present among base stations. An alternate tri-lateration algorithm based on non-linear least square was implemented which significantly drove down the RMSE error by 56%.

Secondly using the default UWB system proved to be very inflexible. During our experiments we found a large number of blind spots while tracking a moving player. It was found that this was due to the lack of base stations seen by the UWB nodes. In order to alleviate this, a time stamp based platform was developed. This system has provisions to share information between the different UWB sensors on the player so as to obtain a location estimate at the required at the 10 Hz update rate.

Finally the ball detection problem was modelled as a proximity based problem. Different proximity based approaches such as charge magnetic inductance, electromagnetic inductance or using ultrasound or ToF sensors were evaluated. It was found that ToF sensor works the best for our application.

7.2 Future Scope

1. The sport platform can be reduced in size.
2. The platform can be further expanded to use a variety of sensors to measure physiological signals.
3. Analytical methods can be applied to make more informed decision (such as substitution of players during a game) based on the positioning information provided by the platform.
4. The signals from an Inertial Motion Unit sensor can be further studied to detect if a player is being fouled or is trying to simulate a game.

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