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FINAL DEGREE PROJECT

Ultra-wideband positioning Systems for industrial environments

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Author: Pablo Recolons Brugueras

Director: Mª Concepción Santos Blanco

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Abstract

This project is about the challenge of obtaining the position of an asset, person, vehicle or animal in industrial environments. This information is, as any relevant parameter, digitalized and used by the computing systems to monitor its status, alert or trigger actions on itself or third parties, store for forensic uses or any other purposes.

The subject has rapidly evolved in the last ten years, with new approaches, none of them perfect yet. Ultra-wideband radio frequency is the technology that I will be using for this proposed methodology of solving this challenge. First I will cover the different alternatives available today, and then the practical implications of deploying a UWB system.

The result will be a proposed architecture and deployment for real world industrial scenarios in which the UWB applies.

1. Introduction

In the last twenty-five years I had the chance of working with different challenges that could be addressed using identification technologies.

In the 90smost solutions involved bar-code tagging and bar-code scanners. Those scanners (readers) were not connected permanently to any computing system, so they had to locally store readings and the databases that were necessary depending on the process, and then connect periodically to un-load readings and load updated databases.

The position of those scanners was very relevant and this process of relating a reading (scan) to a position was triggered by a human action (i.e. associating scanner 1 to room 1, or scanning a positioned tag in a shelf before scanning an item that had to be placed so that they are related). In this case the identification and positioning took place in an asynchronous way.

The emergence of the wireless LAN had a significant impact. Any new information was suddenly available to the WLAN enabled bar-code reader instantly and vice-versa, any new reading could be reflected in the computing systems instantly.

As passive Radio-frequency identification (RFID) became more affordable, RFID started complementing bar-code reading. To the advantages that bar-codes have to offer, RFID adds that the reading distance can be larger, it can do virtually simultaneous readings, and it can store re-writable information.

Both bar-code and RFID technologies are widespread and present in everybody's life, from books in libraries to public transportation passes, products in shops, coupons, animal identification, patients in hospitals, passports, nightclubs, highway tolls and so on.

These technologies address the identification challenge and can give position information for every reading at any reading position. This is enough in many current applications.

When we look for precisions beyond those offered by distances between reading positions, we need real time reading. Those precisions can be necessary for two main reasons: to improve an existing process or to enable a new process. Here is one example of each of the two reasons.

For the improvement of an existing process in a plant, i.e. a truck that goes between point A and B. We could measure the time difference between a RFID reading in point B and A to know the time it took the truck. This can give us information to be analyzed after the action takes place. If we wanted a warning when something has stopped the truck, we would need real time positioning, and gain global efficiency.

For the enablement of new processes in a hospital, i.e. the system could notify the closest free nurse so than a patient in need is assisted as early as possible.

In this project I will be dealing with real time positioning in the industrial environment. In particular, RTLS using UWB, which is the best current technological alternative.

A. Project context

i) The Internet of Things (IoT)

The omnipresence of data connectivity has triggered the appearance of new applications in every field of human activity. New efficient ways to stablish data communication (both in energy and frequency spectrum usage) continue to be developed and put to use.

This ubiquity has allowed that any object, animal, person or element of nature communicates useful information about itself or its surroundings to the digital world for monitoring, decision taking or predictive purposes, and in the opposite direction, that actions triggered in the digital world may be taken in the physical world. Sensors and actuators connected by networks to computing systems help monitor or manage the health and actions of these objects.

By blending physical and digital realms, the Internet of Things (IoT) vastly expands the reach of information technology. The myriad possibilities that arise from the ability to monitor and control things in the physical world electronically have inspired a surge of innovation and enthusiasm. The sweeping changes that IoT can bring to how companies manage physical assets, how consumers attend to their health and fitness, and how cities operate have also inspired visions of a very different future, as well as a good deal of hype. To obtain the greatest benefits of IoT implementations, which require creating highly complex systems and coordinating technology, investment, and talent across both space and time.

People and organizations have the opportunity of taking advantage of this newly available wealth of information to make better and more informed data-driven decisions. In the short term some of this decisions will be based on common sense or the application of rules. In the future, most of them will be more and more based on the result of the application of artificial intelligence.

At a practical level, IoT can be applied to every human and economic activity. IoT will be applied in all cases where there is value creation, such as a transformation of business processes or the enablement of new ones. Examples sectors and type of applications are:

- Human: Health and fitness
- Home: Security and chore automation
- Cities: Transportation and Public health
- Manufacturing: Improve equipment usage and efficiency of operations
- Retail: Automated checkout and omnichannel marketing
- Outside: Logistics and Navigation
- Worksites: Operations efficiency and safety
- Vehicles: Condition-based maintenance and autonomous vehicles
- Offices: Energy and security

One challenge is how connected things can track their own locations. Many uses for the Internet of Things requires knowing where the things are. And this is where RTLS for LBS emerges.

ii) Real time location systems (RTLS) as a key part of IoT

The current and past position of a thing is relevant information that may help take better decisions for itself or for processes taking place anywhere.

Real-time location systems (RTLS) are technology solutions that automatically identify and track the location of objects, people or animals in real time, in most cases within a building such as a warehouse, shipping yard, hospital, or campus.

As in any other parameter of the things being monitored, data about the position at a particular time when it is measured can be relative or absolute, and its precision may be accurate or vague.

These solutions enable organizations to more effectively keep track of where things are, which can help them improve processes they are currently struggling with, such as inventory management. RTLS systems are designed to replace outdated, less efficient solutions such as spreadsheets and clipboards, by automating tasks that are now largely manual and prone to errors.

The RTLS systems are also valuable to businesses because they generate intelligence: Useful data about product and asset movement within facilities, how quickly processes are being completed, and what organizations such as hospitals can do to speed up services. Data gathered by these systems can be stored, analyzed, audited, and assessed by internal parties or external authorities such as public safety organizations.

The term “RTLS” first emerged in the late 1990s, to describe and differentiate a new technology that leveraged the automatic identification capabilities of radio frequency identification (RFID) tags, and provided the ability to view the location of a tagged object on a computer screen. Although similar capabilities had been used earlier by military and government agencies, the technology supporting it had been too costly for commercial purposes.

Some practical uses of Micro-location Technologies are:

1. Finding Things—whether in a Warehouse or at Home: like GPS systems outside. For instance, a warehouse can be mapped helping guide automatic guided vehicles or human workers looking to find parts, tools, or pallets spread throughout the building. Many of this first applications combine RTLS with Augmented Reality applications.

2. Detecting Car Parts and Cars on Parking Lots: i.e. streamlining manufacturing. Sometimes, a carmaker will build a car and everything finished but for one part, say, a seatbelt. Micro-location technology can make locating that car much easier. This capability can also be used within automotive manufacturing facilities to locate tools, spare parts, and workers used to assemble the car. Also, automotive companies can integrate the technology into cars to enable smart parking and other features.

3. Tracking Professional and Amateur Athletes: player and ball statistics and video overlay.

4. Context-Aware Remote Controls: the interface adapts to let you control the music, the radio or whatever device is in range thanks to remote controls designed to take advantage of micro-location technology.

5. Auto-Following Drones and cameras: instead of facial or form recognition by high-resolution cameras, by using a positioned wearable.

6. Preventing Accidents: Cyclists or pedestrians equipped with a positioned tag could communicate with connected to help avoid collisions. The same basic principle can prevent forklift accidents within manufacturing facilities. Employees with tags could communicate their position to connected forklifts. If workers get too close to the forklift, it will automatically stop.

7. Making Hospitals Safer and More Efficient: help clinicians keep track of assets, ensuring that the right products are used with patients. Guide staff doctors and nurses as quickly as possible and can optimize patient flow.

8. Tracking Emergency Personnel and Soldiers: tracking emergency personnel such as firefighters who can be difficult to monitor otherwise when entering buildings filled with flames and thick smoke. The same technology can be used to monitor the position of soldiers on missions and help guide them back to the base.

10. Retail Applications: shopping assistance, shopper behavior.

These are some of the typical Location Based Services (LBS) that have emerged since outdoor and indoor positioning is becoming increasingly available.

iii) The industrial environments

The Industrial Revolution was the transition to new manufacturing processes in the period from about 1760 to sometime between 1820 and 1840. The rapid development of industry brought about by the introduction of machinery. It was characterized by the use of steam power, the growth of factories, and the mass production of manufactured goods.

This transition included going from hand production methods to machines, new chemical manufacturing and iron production processes, improved efficiency of water power, the increasing use of steam power, the development of machine tools and the rise of the factory system.

The Industrial Revolution marked a major turning point in history; almost every aspect of daily life was influenced in some way. In particular, average income and population began to exhibit unprecedented sustained growth. Labour switched from agriculture to the industry. Agriculture itself became industrialized. It is considered that the onset of the Industrial Revolution is the most important event in the history of humanity since the domestication of animals and plants.

The Digital transformation started in the second half of the XXth century and new technologies are being incorporated to every industry as they are becoming more and more affordable and combinable. Not only they bring marginal efficiency, overall they bring innovation to manufacturing and logistics.

The Industrial environments are all those environments that the usage of machinery and mass production, such as manufacturing plants, large warehouses and yards, and so on. They apply to all activities, from fishing, agriculture and mining to aerospace. Typical industrial environments that I consider in this document are: Construction, Ports and Terminals, Mining and Tunnels, Logistics, Heavy industries (foundries,…), Manufacturing Plants, Mining, or Oil and Gas. These will have particular needs. I will not be considering environments such as the Amusement Parks or Cruises (Tourism Industry) or Industrial Cattle Breeding (Food Industry).

The current stage of Industry in the developed world is the beginning of the so called Industry 4.0, which means that industries are adopting automation and data exchange in manufacturing technologies, including cyber-physical systems, the Internet of things and cloud computing. Industry 4.0 creates what has been called a "smart factory". Within the modular structured smart factories, cyber-physical systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. This is the area in which this document applies.

Challenges for deployment of positioning systems into those environments are mainly electromagnetic interference, multipath and the need of very low lag time.

B. Objectives

The main objective of this project is:

- designing an architecture needed for the deployment and usage of the UWB technology in industrial environments for real-time positioning applications (RLTS)
- Requirements are: precision of <50cm, above 99% availability and low lag (under 100ms for real time streams)

Secondary objectives are:

- comparing UWB technology to other technologies currently available
- discussing real world industrial scenarios in which this technology applies
- identifying benefits of RTLS in industrial environments

C. Structure of the project report

In chapter 2 I will go through the features of an industrial environment, what problems we encounter to achieve accurate, fast and reliable positioning, and how to approach the problem with different technologies, including UWB.

In chapter 3 I will describe in more detail how UWB works the algorithms that can be used to obtain the data, its limitations and the devices that we will use for the proposed solutions.

Finally, in chapter 4, I will describe what complementary elements I will use to have a full UWB solution and how to approach several scenarios in order to solve the positioning challenge with the UWB devices.

2. Problem description and technological alternatives

A. Use of positioning in industrial environments

In both manufacturing and logistics, the primary business challenges nearly always include identifying hidden costs, increasing productivity and staff safety.

Indoor/Outdoor positioning systems enable logistics and manufacturing companies to calculate and analyze the location of things indoors. The focus in these areas typically includes visualization of flow, route optimization based on location, and task management using the current location for safety measures. Some applications are:

• Staff tracking: Monitor warehouse workers in real-time to obtain an overview of the coordination. Delegate tasks depending on staff location. Identify excess movement and improve warehouse layout. With staff tracking a warehouse manager can observe a snapshot overview of the operations.

• Dwell time tracking: Track time spent at different locations and reduce wasteful waiting times in operations. Compare total idle time over periods or workforces. Measure the travel time between assembly stations to discover bottlenecks and identify best-practices.

• Scenario replays: With all tracking data stored, management can replay all forklift movements during a specific time interval, for instance, in forensics to identify how accidents or other events happened and learn from them. Scenario replays also can help analyze how operations react to unusually high workloads.

• Asset management: Track moveable assets to reduce time wasted on searching for a piece of equipment. Keep track of every piece of goods in a warehouse. Identify the goods that move often and those that are idle for long periods of time. Improved knowledge and control of equipment inventory can vastly reduce waste at an assembly or warehouse site.

• Reliable location data: In vast warehouses and industrial sites, reliable (available more than 99% of the time) location data is essential and helps improve productivity.

There are more applications, in chapter 4 I will see to approach them using micro-location with UWB technology.

B. Technical challenges of positioning in industrial environments

Industrial environments present several challenges that will limit the use of many of the technologies that I will be examining in this chapter.

- The presence of heavy duty machinery, electrical transformers, proprietary or non-proprietary RF communication systems, and so on produces electromagnetic interference, which is a very important factor that needs to be taken into account when dealing with any particular implementation.
- Lag time in the detection on computing of the position. Positioning information may be critical in fast vehicles or robots. Factors such as the technology used to obtain raw data (power, time of flight or any other), the channel used, the place where computation of the algorithms take place, and so on, take place, all sum up. Computations may be made on a central server or on any individual devices. Performing the computations on the device allows for the positioning to work even if there are no Internet connection available. The goal is to reduce lag times below 100ms.
- NLOS propagation may be an issue whenever RF is used. Heavy duty machines and infrastructure may be very bulky and create many pockets of space where LOS cannot be possible. Metal and liquids attenuate RF signals significantly. Multipath is also present in almost all environments has to be taken into account for RF raw data intake.
- Dust, temperature, smoke, high noise levels, high and low lighting conditions, grease and debris, and presence of explosive gases and liquids are also important factors. Industrial grade electronics and, in some cases ATEX certified devices are necessary.

I will take some of those challenges into account in the next point covering technological alternatives.

C. Technological alternatives

I am going to go through some of the most used indoor positioning technologies. Some of these technologies are based on RF, and other are based on other measuring methods such as optical, laser, acoustic, and so on.

I will briefly describe them and their current advantages and disadvantages and, at the end of the chapter, I will summarize with a chart of their performance in the key aspects of positioning.

i) Radio alternatives

A. RFID

An RFID (Radio Frequency Identification) system consists of a reader with an antenna which interrogates nearby active transceivers or passive tags. Using RFID technology, data can be transmitted from the RFID tags to the reader (also known as RFID scanner) via radio waves.

Typically, the data consist of the tag's unique ID (i.e. its serial number) which can be related to available position information of the RFID tag. The most frequently employed positioning principle is that of proximity, also known as CoO (Cell of Origin), e.g. the system indicates the presence of a person wearing an RFID tag. Thereby, the accuracy of an RFID system is highly depending on the density of tag deployment and the maximal reading ranges. Alternatively, the Received Signal Strength Indicators (RSSI) can be used for coarse range estimation in order to apply multilateration techniques. Time of Arrival (ToA) distance estimation on RFID has been proven difficult to achieve. In order to measure the distance between a reader and a tag at a resolution of better than one meter, a bandwidth of at least 10 kHz must be used and multiple observations need to be averaged. The standard case of RFID positioning based on ToA distances relies on observations from a single tag, where the position determination is carried out in combination with Angle of Arrival (AoA) measurements from that tag. Also Phase of Arrival (PoA) methods have been proposed for RFID. Fingerprinting(FP) based on pre-measured signal maps can also be applied. Readers are able to scan several tags at high data rates up to 10 Hz.

Generally, RFID systems can be unobtrusive to the user by integrating the tags in the pavement, under the carpet or in the walls without direct line of sight, since the radio waves have the ability to penetrate solid materials to some extent. The higher the frequency, the more the signal suffers from attenuation. The typical frequency ranges are categorized as Low Frequencies (LF) at 30 kHz to 500 kHz, High Frequencies (HF) at 3 MHz to 30 MHz, Ultra-High frequencies (UHF) at 433 MHz & 868 MHz to 930 MHz and microwaves (SHF) at 2.4 GHz to 2.5 GHz & 5.8 GHz.

However, as RFID moves to item and device tagging, the probability oftags disclosing personally identifiable information has become a primary privacy concern for users. On the other hand, the unique identification of RFID can be used for security to control building access or for payment systems allowing customers to pay for items automatically. When scaling an RFID system to large numbers in multiple facilities with geographical distribution, a challenge for data management and configuration arises.

Passive RFID systems solely rely on inductive coupling and therefore don't require batteries. The principle of inductive coupling allows the tags to receive sufficient energy in the form of RF waves from the nearby RFID scanner to transmit their codes back to the scanner. Passive tags can be applied for waypoint navigation based on a reference grid of ID markers whose locations are accessible from a database.

The advantages of using passive RFID tags for positioning are their small size, high level of ruggedness, relatively inexpensive installation and low maintenance needs since they have no batteries. Therefore, passive tags are suitable for subsurface embedding in building material.

As the main drawback, the detection range is usually limited to 2 m, which demands dense deployment of tags. The attenuation for embedded tags increases with the frequency, e.g. the application for concrete embedded tags is prohibitive for frequencies above 2.4 GHz. Below 100 MHz the attenuation of embedded tags is low and comparable to that of free space, but frequencies below 300 MHz are unsuited for read ranges above 1 meter due to inductive coupling as a phenomenon of near-field operation. The penetration of electromagnetic waves in concrete depends on the use of integrated metal fibers, the moisture content of walls, floors and ceilings and the angle of incidence of the radio wave.

An active RFID system consists of deployed RFID scanners which interrogate active radio transceivers equipped with internal battery power. In contrast to passive tags the need for batteries make active transceivers heavier and costlier, but enables long detection ranges of 30 m or more. The active RFID technology can be used for positioning, where the location estimation is typically carried out by fingerprinting on RSSI.

Passive tags have shown to be applicable for vehicle, arrays of passive RFID tags which have been deployed under the carpet to provide route guidance for visually impaired and blind people. The readings depend on the coupling and may take seconds.

Most RFID systems rely on proximity detection of permanently mounted tags to locate mobile readers. Therefore, the accuracy of an RFID system is directly related to the density of tag deployment and reading ranges. Some long-range active RFID systems can also use signal strength information to improve the localization accuracy. RFID can be combined with IMU in order to correct the drift which IMUs have. The main application of RFID location systems is route guidance for pedestrians

B. BLE

Bluetooth is a wireless standard for Wireless Personal Area Networks (WPANs). The Bluetooth standard is a proprietary format managed by the Bluetooth Special Interest Group. The advantage of using Bluetooth for exchanging information between devices is that this technology is of high security, low cost, low power and small size.

The Bluetooth SIG identifies a number of markets for low energy technology, particularly in the smart home, health, sport and fitness sectors. Its advantages include:

- low power requirements, operating for "months or years" on a button cell
- small size and low cost
- compatibility with a large installed base of mobile phones, tablets and computers

Bluetooth works in the 2.4GHz range, which may be crowded in some scenarios. Its latency for connection can be up to several seconds, which is a problem. Standards and intrinsic characteristics of the protocol do not favor conventional time-of-flight based positioning methods. RSSI measure for positioning is not very precise and requires using several channels and repeated measures for enhanced accuracy. Cell of Origin (CoO) method is normally applied as the basic positioning principle, or RSSI with fingerprinting to achieve sub-room accuracy.

C. Wifi

Existing Wi-Fi networks may be used to provide real-time location visibility. Wi-Fi tags track and report on the movement of assets and people and the status of staff safety alarms and temperature sensors. Advanced Wi-Fi RTLS solutions use the network and its signal strength readings to calculate a number of probable locations on a virtual map, comparing tag readings against a stored database of Wi-Fi readings or received signal strength indicators (RSSI).

The use of WLAN signals is a tempting approach, since WLAN access points are readily available in many indoor environments and it is possible to use standard mobile hardware devices. The range of 50 m to 100 m which is typically covered by WLAN outreaches that of Bluetooth or RFID. Another advantage of using WLAN is that line of sight is not required. ToA, TDoA or AoA methods are less common in WLAN due to the complexity of time delay and angular measurements. The most popular WLAN positioning method is to make use of RSSI (Received Signal Strength Indicators) which are easy to extract in 802.11 networks and can run on off-the-shelf WLAN hardware. Therefore, WLAN positioning systems have become the most widespread approach for indoor localization. In general, the use of RSSI in combination with WLANcan be subdivided into four strategies: Propagation modeling, Cell of Origin (CoO), Fingerprinting (FP) and multilateration.

Fingerprinting based on RSSI values is the prevalent method of using WLAN for positioning. Depending on the density of calibration points, fingerprinting reaches accuracies of 2 m to 50 m. The fingerprinting method is particularly of commercial interest, because off-the shelf devices can be used. Experiments on WLAN time-of-arrival distance measurements have proven to be of poor quality due to multipath and low resolution of the clocks. Using RSSI for distance estimation in indoor environments has also proved unreliable due to an irregular dependency between attenuation and distance in indoor environments.

D. Zigbee

ZigBee Mesh networks may be used for RTLS. Zigbee networks rely on low data rate, wireless personal area networks (LR-WPAN) using the IEEE 802.15.4 standard. ZigBee tags send location data to a network of sensor nodes plugged into wall outlets for power. These networks are often referred to as “meshed” because they use a series of nodes to communicate with one another and with a main node or hub. ZigBee networks are ideally suited for short-range operations and do not require a significant amount of power. The plug-and-play aspect of a ZigBee network is its most appealing feature. These systems are also not meant to handle high volumes of tracked items due to bandwidth issues. Interference issues have also been reported between ZigBee networks and Wi-Fi networks, because ZigBee nodes share their channel spectrum with 802.11 standard access points, impacting WLAN applications.

Most ZigBee interference problems are challenging to predict because each facility’s topology and application ecosystem is different. Given the known interference issues with ZigBee networks, it is important to consider asking for an onsite Proof of Concept to mitigate interference risks associated with ZigBee RTLS.

E. UWB

I will cover UWB extensively in the next chapter. As a short introduction, UWB is an RF signal occupying a portion of the frequency spectrum that is greater than 20% of the center carrier frequency, or has a bandwidth greater than 500MHz. UWB is a communication channel that spreads information out over a wide portion of the frequency spectrum. This allows UWB transmitters to transmit large amounts of data while consuming little transmit energy. UWB best approach to positioning is by using the time difference of arrival (TDOA) of the RF signals to obtain the distance between the reference point and the target

F. Low Power WAN

Low power networks are relatively new. They appeared as a need for the Internet of things to develop. Their goal is to achieve a long range low power network so that sensor's batteries last months or years (depending on the duty cycle). There are several protocols in use as of today. The most present in real deployments are Sigfox and LoRa. In particular, LoRa's nodes have already implemented this geolocation ability. It gives resolutions of the tens of meters.

G. Cellular based

Global System for Mobile Communications (GSM) networks are available in most countries and can outreach the coverage of WLAN with lower positioning accuracy.

GSM operates in the licensed bands and prevents interference from other devices operating at a similar frequency (unlike WLAN). It is possible to use indoor positioning on a mobile cellular network if the building is covered by one or more base stations with strong RSS [3]. The most common method of GSM indoor positioning is fingerprinting which is based on the power level (RSS).

H. Pseudolites

GNSS are global navigation satellite systems (GPS and GLONASS are operational, Galileo and BeiDou will be globally available in the next years) which provide outdoor positioning.

The satellites contain atomic clocks that are precise to within a billionth of a second, and based on this data the receivers know how long it takes for the signal to reach the receiver on earth. By using three satellites, GPS can calculate the longitude and latitude of a receiver based on where the three spheres intersect.

GPS based Real Time Location Systems are severely degraded when used indoors and they also consume significant amounts of energy making them impractical for use in settings where tags do not receive a continuous power supply or are not getting charged on a daily basis.

Improvements.

The term 'pseudolite' is an accepted short form for pseudo-satellites, which are land-based beacons that generate pseudo-noise codes similar to those transmitted by GNSS. A pseudolite system also includes mobile receiver units (rovers) whose positions are estimated from distance measurements to the pseudolite beacons which are usually deployed at known positions. The main purpose of pseudolites is to support GNSS with additional ranges in situations where satellite signals are blocked, jammed or simply not available.

Legal broadcasting of GNSS signals is very limited. The coverage area of a pseudolite system can span up to tens of kilometers, with its limitation mainly driven by the availability of line of sight between pseudolites and rovers. The received power from pseudolites is orders of magnitude stronger compared to the received signal strength of satellites. A combined pseudolite receiver can acquire and track GNSS and pseudolite signals. This functionality provides an extended positioning solution for seamless transition between indoor and outdoor environments.

Time synchronization remains a costly and complex task for pseudolite range measurements. This is particularly the case in deep indoor environments where access to atomic clocks of the GNSS satellites is not available.

Pseudolites can also use signals different to GNSS, using a dedicated signal infrastructure which is similar – but not identical – to that of GNSS. An advantage is that license-free frequency bands can be used with better prospects of commercialization. Such systems have an architecture that usually includes distance estimation by pseudo ranges and carrier phase measurements.

I. NFER

The Near-Field Electromagnetic Ranging (NFER) uses the properties of radio waves, where the near field encompasses an antenna or, more generally, any electromagnetic radiation source with an approximate sphere of radius 1/6 of the radiation. In NFER, the distance from a small transmitter antenna is derived from the phase relation between the electric and the magnetic field components of an electro-magnetic field. The receiver unit must be able to receive the two signal components separately and compare their phases. Close to the antenna, these components have a maximal phase difference of 90°. Since the phase difference decreases with the distance to the antenna it can be used for range determination within a certain proximity to the antenna. As a major advantage NFER does not require synchronization or signal modulation. Secondly, if low frequencies around 1 MHz are used, the signals have the potential to penetrate walls. On the other hand, the use of low RF frequencies requires large receiver units since an efficient receiver antenna needs to be within a quarter-wavelength in size.

ii)Other alternatives

A. Laser

There are several ways of approaching indoor positioning with Laser technologies. Laser tracking, laser scanning and laser radar are some of the most common. The advantages are as high sampling rate, accuracy and high angular resolution, fair range resolution, etc. Some of the drawbacks are that the information is restricted to a plane, the sensor is quite expensive, device size, some materials may appear as (almost) transparent for the laser (such as glass), etc.

Due to high instrument costs and limitation to a single room at a time, these systems are rarely applied to positioning, but are essential tools for many industrial industry needs, surveying and 3D modeling.

B. Ultrasonic

An ultrasound wave is “a mechanical wave that is an oscillation of pressure transmitted through a medium”. It does not interfere with electromagnetic waves and has relatively short range. Ultrasonic positioning systems leverage building material and the air as a propagation medium. The relative distance between the different devices can be estimated using time of arrival (ToA) measurements of ultrasound pulses traveling from emitters to the receivers.

The emitter’s coordinates can be estimated by multilateration from three (or more) ranges to some fixed receivers (deployed at known locations).

The main problems are NLOS conditions, multipath propagation, the exposition of the sound transducer at the surface, and limitation inside a room.

C. Infrared

Infrared (IR). Infrared wireless communication makes use of the invisible spectrum of light just below the red edge of the visible spectrum, which makes this technology less intrusive than indoor positioning that is based on visible light. IR can be used in two different ways; direct IR and diffuse IR. Infrared Data Association (IrDA) is an example of direct IR that uses a point-to-point ad-hoc data transmission standard designed for very low-power communications. IrDA requires line of sight communication between devices over a very short distance and up to 16Mbps. On the other hand, diffuse IR has stronger signals than direct IR, and therefore it has a longer reach (9–12 m). Diffuse IR uses wide angle LEDs which emit signals in many directions. Thus, it allows one to many connections and does not require direct line of sight. Proximity, differential phase-shift, and angle of arrival (AoA) positioning methods are frequently used with Infrared technology.

D. Image Based Technologies.

Image based indoor positioning technologies, which are sometimes called optical methods, include camera and computer vision based technologies. Different types of camera can be used such as mobile phone cameras, omni-directional camera, and three dimensional cameras; however, their performance varies due to the amount of information that can be extracted from their images. The success of image based technologies relies on different factors, such as; improvement and miniaturization of actuators, advancement in the technology of the detectors, an increase in the data transmission rates and computational capabilities and development of algorithms in image processing. Image based positioning systems can be categorized into two main categories; egomotion systems which use a camera's motion relative to a rigid scene to estimate the current position of the camera and static sensor systems which locate moving objects in the images.

E. Dead Reckoning

In dead reckoning, an object can approximately determine its current position by knowing the past position and the velocity with which it moves. Dead reckoning is a navigation technology that needs to begin with a known position; and will then add and track changes thanks to its Inertial Navigation Systems (INS). These changes can be in the form of Cartesian coordinates or velocity. With the right number of absolute position updates, dead reckoning's linearly growing position errors might be contained within pre-defined bounds. In order to improve accuracy and reduce error, dead reckoning must use other methods to adjust the position of the object after each interval.

An INS is an electronic device which provides estimates of position, velocity and orientation from an IMU. The custom IMU consists of three orthogonally arranged accelerometers (motion sensors), three gyroscopes (angular rate sensors) and/or a magnetometer (3 perpendicular sensors for measuring the strength and/or direction of a magnetic field). If the initial position and orientation are known, subsequent positions, orientations and velocities (direction and speed of movement) of the moving platform can be updated continuously via Dead Reckoning (DR) without the need for external reference positions. The main argument to use INS for pedestrian navigation arises from independent operability – at least temporarily – without external infrastructure, making navigation possible in environments, where the installation and maintenance of such infrastructure is not affordable such as public places.

The most commonly used form of indoor location in public places for smartphones is the use of dead reckoning combined with other information, such as the information obtained from Radio signal sensors that detect the Wi-Fi and Bluetooth emissions in the phone. The phone can determine

which access points or beacons are within range and can evaluate signal strength. When comparing signals from radio signal sensors to a map of locations in the building where different radio signals should be heard, a rough understanding of the location of the smartphone is given.
The combination of the information from the movement sensors, the radio sensors and a map of the building, is known as “sensor fusion.” Sensor fusion is the technology of combining information from multiple complementary sources to create one estimate of, for example, a position. This joint position estimate provided through sensor fusion is more precise and reliable than an estimate made form information that is treated separately.

	Distance	Detection beyond walls	Fingerprinting	Accuracy	Real time	Resistance to Interference	Equipment size	Environment independence	Additional Infrastructure independence	Autonomy
RFID	x	x	x	x	x	xxx	xxxx	x	x	xxxx
BLE	xx	xx	x	xx	x	xx	xxxx	x	xx	xxxx
Wifi	xx	xxxx	x	xx	x	xx	xx	x	xxx	xx
Zigbee	xx	xxx	xxx	xx	x	x	xxxx	x	x	xxx
UWB	xxx	xxxx	xxxx	xxxx	xxxx	xxx	xxxx	x	x	xxxx
LPWAN	xxxx	xxxx	xxxx	x	x	xxx	xxxx	xxxx	xxxx	xxxx
Cellular Based	xxxx	xxxx	xxxx	xx	xx	xxxx	xx	x	xxxx	xx
Pseudolites	xxxx	xxxx	xxx	xx	xxxx	xxxx	xxx	x	x	xx
NFER	xx	xx	xx	xxx	xxxx	xxx	x	x	x	x
Laser	x	x	xxx	xxxx	xxx	xxxx	x	x	x	x
Ulrasonic	x	x	xxx	xxx	xxx	xxx	x	x	x	xx
InfraRed	x	x	xxx	xxx	xxx	xxx	x	x	x	xx
Image Based	x	x	xxx	xxx	xx	xxx	x	xxxx	x	x
Dead Reckoning	xxxx	xxxx	xxxx	xx	xxx	xxx	xxxx	xxxx	xxxx	xxx

	Typical Measurement technique	Pros	Cons
RFID	Proximity, RSS	Penetrate solid, non-metal objects; does not require LOS between RF transmitters and receivers	The antenna affects the RF signal, the positioning coverage is small, the role of proximity lacks communications capabilities, RF communication is not inherently secure
BLE	Proximity, RSS	Does not require LOS between communicating devices; highly ubiquitous; it is also built into most smartphones, personal digital assistants, etc.	The greater the number of cells, the smaller the size of each cell and hence better accuracy, but more cells increase the cost; requires a host computer to locate the Bluetooth radio. 2.4 GHz spectrum, radio interference is likely
Wifi	RSS	Use existing communication networks that may cover more than one building; the majority of devices available nowadays are equipped with WLAN connectivity; WLANs exist approximately in the majority of buildings; LOS is not required	A major drawback of WLAN fingerprinting systems is the recalculation of the predefined signal strength map in case of changes in the environment (e.g., open/closed doors and the moving of furniture in offices)
Zigbee	RSS, Phase Shift Measurement	Its sensors require very little energy and low cost	2.4GHz, vulnerable to interference. Lag time.
UWB	ToA,TDOA	High accuracy positioning, even in the presence of severe multipath, effectively passes through walls, equipment, and any other obstacles; UWB will not interfere with existing RF systems if properly designed	High cost of UWB equipment [27]; although UWB is less susceptible to interference relative to other technologies, it is still subject to interference caused by metallic materials
LPWAN	RSS	Low power	Networks available in some geographies only. Low accuracy.
Cellular Based	RSS	No interference with devices that operate at the same frequency; the hardware of customary mobile phones can also be used	Low reliability due to varying signal propagation conditions
Pseudolites	RSS	They allow to extend the coverage area much farther to several kilometers and provide great flexibility in deployment that can be optimized for a particular application and they are also compatible	They are negatively affected by multipath, signal interference among pseudolites, weak time synchronization due to less accurate clocks within pseudolites and carrier phase ambiguities

		with existing GPS receivers	
NFER	Proximity, Differential Phase-shift	Not vulnerable to obstacles due to low frequency	Bulky and power hungry
Laser	ToA, TDOA	Precise	Does not penetrate walls. Big size. Needs power.
Ulrasonic	ToA, TDOA	Does not require LOS; do not interfere with electromagnetic waves	Does not penetrate walls, therefore it is typically used in small spaces such as one room; IR communication is blocked by obstacles that block light which includes almost everything solid [25]; requires LOS between sender and receiver when using direct IR; One problem with diffuse infrared systems is their poor performance in locations with direct sunlight or fluorescent lighting because the infrared emissions (of the light sources) may interfere with the signals
InfraRed	Proximity, Differential Phase-shift, AoA	Since IR signals cannot penetrate through walls, it is suitable for sensitive communication because it will not be accessible outside a room or a building [25	Does not penetrate walls, therefore it is typically used in small spaces such as one room; IR communication is blocked by obstacles that block light which includes almost everything solid [25]; requires LOS between sender and receiver when using direct IR; One problem with diffuse infrared systems is their poor performance in locations with direct sunlight or fluorescent lighting because the infrared emissions (of the light sources) may interfere with the signals
Image Based	Pattern recognition	They are relatively cheap compared with other technologies such as ultrasound and ultra wideband technologies	Requires LOS, coverage is limited
Dead Reckoning	Tracking	Does not require additional hardware such as sensors	The DR calculates only an approximate position

So, after going through all the options, UWB is the technology that offers us a better balance and has no major problem in industrial environments.

3. UWB technology and devices

The precursor technology of UWB is referred to as a base-band, impulse, and carrier-free technology. The US Department of Defense was the first to use the term ultra-wideband. UWB became commercially available in the late 1990. UWB radio is a method of spectrum access that can provide high speed data rate communication over the personal area network space. UWB is based on transmitting extremely short pulses and uses techniques that cause a spreading of the radio energy (over a wide frequency band) with a very low power spectral density. This high bandwidth offers high data throughput for communication. The low frequency of UWB pulses enables the signal to effectively pass through obstacles such as walls and objects.

There are three main application areas for using UWB: (1) communication and sensors; (2) positioning and tracking; and (3) radar. UWB positioning techniques can in fact give real-time indoor precision tracking for several applications such as mobile inventory and locator beacons for emergency services, indoor navigation for blind and visually impaired people, tracking of people or instruments, and military reconnaissance. UWB signals provide accurate position and location estimation for indoor environments.

The high bandwidth and extremely short pulses waveforms help in reducing the effect of multipath interference and facilitate determination of TOA for burst transmission between the transmitter and corresponding receiver, which makes UWB a more desirable solution for indoor positioning than other technologies. The duration of a single pulse determines the minimum differential path delay while the period pulse signals determines the maximum observable multipath delay in order to unambiguously perform multipath resolution. In addition, the low frequency of UWB pulses enables the signal to effectively pass through obstacles such as walls and objects which improves accuracy. In fact, UWB provides a high accuracy rate that can minimize error to sub-centimeters. Therefore, UWB is considered to be one of the most suitable choices for critical positioning applications that require highly accurate results.

UWB technology, unlike other positioning technologies such as infra-red and ultrasound sensor, does not require a line-of-sight and is not affected by the existence of other communication devices or external noise due to its high bandwidth and signal modulation. Furthermore, the cost of UWB equipment is low and it consumes less power than other competitive solutions.

A. Signal Modulation

Signal modulation is the process of carrying information on the impulse signal (the carrier signal) by modifying one or more of the signal properties. In general, signal modulation can be categorized based on the signal state into three categories; binary modulation, ternary modulation, and M-ary modulation. Signal modulation can also be categorized based on signal properties that need to be modified into four categories; amplitude modulation, frequency modulation, phase modulation, and hybrid modulation.

Signal modulation is a crucial phase in signal transmission that can greatly improve the quality of transmitting signals to achieve certain quality criteria. For example, UWB signals are usually transmitted in the existence of other signals in the air as well as reflected signals that may cause multi-path interference. Thus, UWB must have high modulation efficiency, as signals must be recognized correctly in the presence of noise and interference [45].

Various signal modulations that are used for UWB, such as pulse position modulation (PPM), on-off Keying (OOK), pulse amplitude modulation (PAM), and pulse width modulation (PWM). Signal modulation is utilized to enhance the accuracy of UWB localization. Time-hopping spread spectrum (TH-SS) impulse radio in UWB can be used to solve multipath problems and generate UWB signals with relatively low computational cost. Other modulations can also be used by UWB, such as pseudo random (PR) time modulation, binary phase shift keying (BPSK), time-hopping binary phase shift keying (TH-BPSK), time-hopping pulse position modulation (TH-PPM), and minimum-shift keying (MSK).

B. UWB Positioning Algorithms

UWB technology is well suited for indoor positioning applications. In order to employ this technology, different positioning algorithms have been developed in which position information is extracted from radio signals traveling between the reference nodes and target node in addition to the position information of the reference nodes. There are many positioning algorithms that can be classified into five main categories based on some estimating measurements: (1) time of arrival (TOA); (2) angle of arrival (AOA); (3) received signal strength (RSS); (4) time difference of arrival (TDOA); and (5) hybrid algorithm

1) AOA-Based Algorithms

In the AOA technique, the estimation of the signal reception angles, from at least two sources, is compared with either the signal amplitude or carrier phase across multiple antennas. The location can be found from the intersection of the angle line for each signal source. AOA estimation algorithms are very sensitive to many factors, which may cause errors in their estimation of target position. Furthermore, AOA estimation algorithms have a higher complexity compared to other methods. For instance, the antenna array geometry has a major role in the estimation algorithm. Increasing the distance between the sender and receiver may decrease the accuracy.

2) TOA-Based Algorithms

TOA is based on the intersection of circles for multiple transmitters. The radius of those circles is the distance between the transmitter and receiver. This distance is obtained by the calculation of the one-way propagation time between them. The time synchronization of all transmitters is required whereas the receiver synchronization is unnecessary; any possibility of significant delay must be accounted for during calculation of the correct distance.

3) TDOA-Based Algorithms

TDOA is based on measuring the time difference of arrival of a signal sent by an object and received by three or more receivers. In this manner, the location of the object (transmitter) will be determined. Also, the scenario can be flipped so a single receiver can determine the target location by measuring the delta in arrival times of two transmitted signals. Typically, only one transmitter is available that requires the multiple receivers to share the data and cooperate to determine the location of the transmitter. This cooperation requires significant bandwidth in comparison with other algorithms.

4) RSS-Based Algorithms

In RSS-based algorithms, the tracked target measures the signal strength for received signals from multiple transmitters in order to use signal strength as an estimator of the distance between the transmitters and receivers. This way, the receiver will be able to estimate its position relative to the transmitter nodes. RSS is sensitive to multipath interference and a small-scale channel effect that causes a random deviation from mean received signal strength, so it not the right estimation method for indoor positioning systems. On the other hand, RSS-based algorithms have some advantages over other algorithms which make them attractive in some cases. In such algorithms, the mobile tags act as receivers only and thus rely on the strength of received signals from multiple transmitters to find their positions. In this manner, RSS-based algorithms tend to have less communication traffic which helps in improving channel access control and positioning accuracy. Also, less communication traffic helps to overcome limitation on the number of tags in use, as the mobile tags are receivers only. There is no limitation on their numbers.

RSS-based algorithms can be categorized into two main types: trilateration and fingerprinting. Trilateration algorithms use RSS measurements to estimate the distances to three different reference nodes and hence estimate the current location.

On the other hand, fingerprinting requires collecting a dataset of RSS fingerprints of a scene, which is later used to match online measurements with the closest fingerprint in the dataset in order to estimate the location.

5) Hybrid-Based Algorithms

When multiple positioning techniques are used, they can complement each other or target different parts of the site that fit with their strengths. Overall accuracy will increase as well as complexity and cost

Regarding positioning in a two-dimensional space, the TDOA algorithm requires at least three properly located gateways, whereas the AOA algorithm requires only two gateways for location estimation. In terms of accuracy, small errors in angle measurement will negatively impact accuracy when the target object is far away from the gateway. TDOA and AOA location algorithms can be combined in one algorithm in which they complement each other; such an algorithm has advantages achieving high location accuracy.

TOA and TDOA have higher accuracy relative to other algorithms because of the high time resolution of the UWB signals. Clock synchronization and clock jitter are important factors that affect the accuracy of the TOA algorithm because clock synchronization is needed between the nodes to estimate the time of arrival accurately. On the other hand, TDOA is a more effective solution if there is no synchronization between the node and the reference nodes when the reference nodes are synchronized among themselves.

Given the constraints in our target applications, it is found that TdOA Is the best alternative due to the speed of calculation, which minimizes lag time (well under 100ms).

C. Strengths and weaknesses of UWB

One advantage of using UWB is that it is license-free because of its low power. UWB is not classified as radio equipment because its low power signal does not interfere with most of the existing radio systems.

UWB consumes low power in comparison with other positioning technologies that enable power efficiency for better battery life of devices. UWB has strict duty cycle on the radio in order to minimize the baseline power consumption. This is very advantageous to our purposes for all assets which are not attached to a power supply.

UWB has a very high level of multipath resolution because of its large bandwidth. Its very short pulses offer an advantage in terms of resolvability of multipath components. That is key for a good performance in the industrial environments targeted here. Many received signals in an environment that are characterized by multipath is a superposition of the delayed replicas of the signal. This has been avoided in UWB because the reflections from objects and surfaces near the path between the transmitter and receiver tend not to overlap in time because of the very short pulses of UWB. This means UWB has a desirable direct resolvability of direct multipath components.

On the other hand, there are a few As in any RF technology, there is a possibility of interference with nearby systems, in this case those that operate in the ultra-wide spectrum due to misconfiguration

Although using very short pulses in UWB has many advantages, the UWB receiver requires signal acquisition, synchronization and tracking to be done with very high precision in time relative to the pulse rate. These steps are time-consuming. There are some techniques for reducing this time such as using a preamble sequence for rapid acquisition. We will be using such preambles as described in point G.

The design and implementation of antennas for UWB systems can be more challenging than the bandwidth and variable conditions of operation. This may add some limitations to UWB systems in comparison with conventional RF. In our case the tag antenna will have an area of 0.5cm^2.

D. UWB devices

After studying the different options in the UWB device market, the available options are fully fledged systems, including electronics, antennas and algorithms. Around mid-2014, one chip manufacturer, Decawave, launched a UWB chip, DW1000, together with the information necessary to create a UWB system. This chip provided a stepping stone and a baseline for many companies that were already into UWB or similar systems.

In 2015 my partners and I, looked into the opportunities this chip gave us in order to create a system (without the investment in hardware that was needed to create such a chip) that would suit industrial needs. We partnered with other European companies to develop a hardware/software combination using this chip. As a result, we have availability to a hardware solution using the Decawave DW1000 UWB ScenSor Chip (see specifications in [8]).

The UWB RTLS devices that will be used in the proposed deployment are two main elements, all using the DW1000 chip, the Gateway and the Tag.

i) UWB Gateway

Gateways are the devices that will be installed as infrastructure. Any traceable device has to be within coverage of at least 3 gateways.

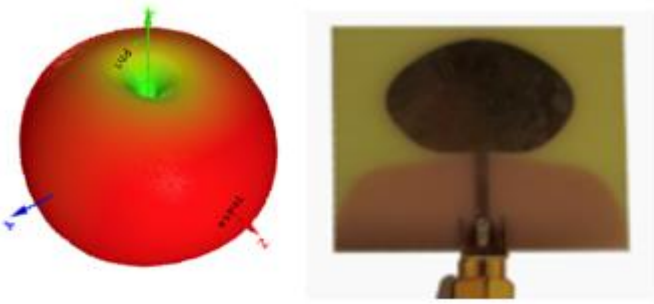
All Gateways have the same basic functions (detecting and gathering data from Tags) depending on the type of positioning algorithm in use. There is one particular type of Gateway, the Master, which communicates with the rest of Gateways in coverage via the UWB radio (for minimal deployment costs) and runs the algorithms to calculate the position.

The Master is the only Gateway that needs connection to the Backhaul, via Ethernet, passing on all the raw data obtained from the cluster of Gateways in every area.

Picture 1: Gateway board

A network can contain multiple Masters to support all required Messages between tags and Gateways are routed via the Master and pre-filtered to eliminate duplicates. The main features are:

- Algorithms supported are trilateration via TDOA (time difference of arrival) and TWR (two way ranging).
- Master manages up to 20 Gateways.
- Coverage is typically up to 5.000 m2 indoor and 20.000m2 outdoor for one cluster
- Remote configuration management
- Firmware update.
- Position and timing auto-calibration feature.



Picture 2: UWB antenna and radiation diagram.

As for the technical specifications:

- 2D and 3D RTLS Indoor/outdoor localization reference.
- Ethernet with PoE, backup battery, 9-30V PSU.
- Decawave DW1000 IC, Cortex M4F 120 MHz 256 kB MCU.
- UWB antenna
- 9.30VDC power supply.
- Optional ISM 2.4 GHz radio for long range backhaul
- Dimensions: 80x60x36mm
- Two enclosures available: Indoor and IP65 for outdoor
- 350mAh LiPo backup battery – rechargeable
- Status: 3 red/green LED indicators.

For industrial environment, electronics will have to be at least of industrial grade (-40°C to 85°C). The enclosure plays an important role in industrial environments. It must be IP67 compliant for outdoor and weather-proof environments, with enough space for additional accessories, such as emergency battery, alternative antennas or power converters. Features heavy duty connectors, UV and impact protection. It may be installed on a pole, wall or surface.

I will describe the basic operation of the whole UWB subsystem later in the chapter.

ii)UWB tags

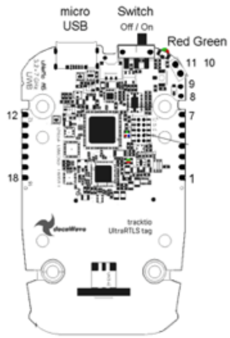
Tags are battery powered items that are attached to the assets. They may include sensors to send additional information to the position.

All the data related to tag ranging and position, sensor status, firmware upgrades and other custom data is exchanged over the UWB Network. Tags may have actionable inputs such as buttons, and also display information or reproduce sounds with leds or buzzers. Industrial needs usually require IP67 and ruggedized form factors so that the tags can be worn by people or attached to assets or vehicles.

Picture 3: Ruggedized enclosure for assets and asset/worker enclosure.

These tags have the following features, using the same UWB chip:

- Wireless Transceiver Module based on Decawave's DW1000 IC
- IEEE802.15.4-2011 UWB compliant
- Precision of 10cm indoors, even while moving at up to 5m/s
- High data rate communications. Up to 6.8Mb/s achieved in Wireless Sensor Networks (WSN)

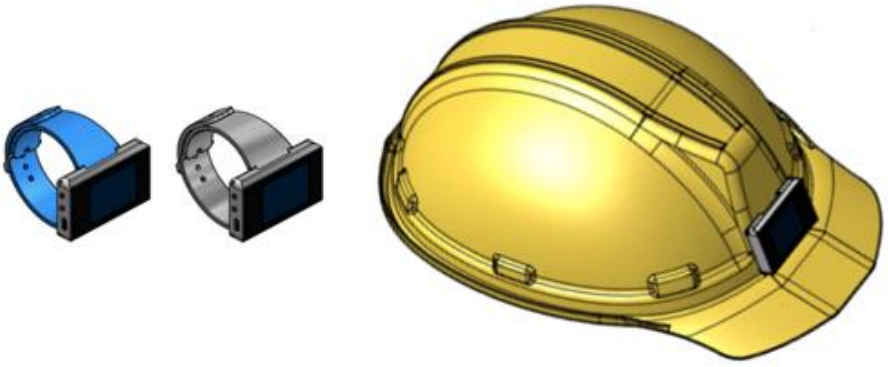


Picture 4: UWB Tag

Its technical specifications are:

- CPU: Cortex M4120MHz + memory
- 1 user button (alarm, etc.)
- signal LEDs
- Battery
- UWB transceiver + antenna
- Extra options: IMU (gyro accmagn.), BLE, Memory, Buzzer, Qi charger, Pressure sensor, Temperature Humidity sensor

The enclosure for industrial assets needs to be rugged and IP67 compliant (dust and water tight).

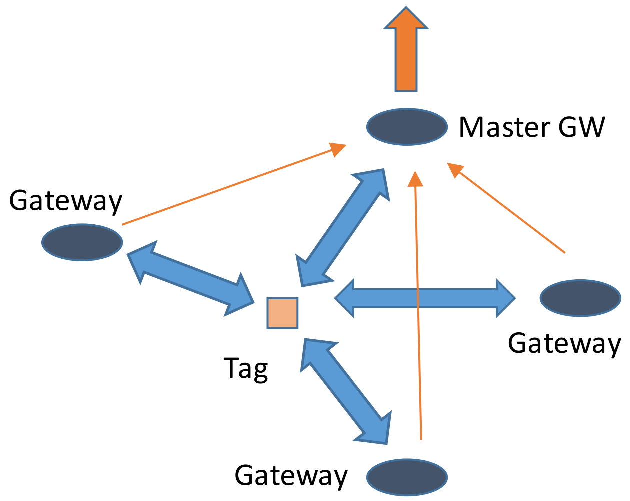


Picture : Wristband and helmet mounted UWB Tag.

iii) RTLS subsystem communication flow

Tags are self registered into Gateways.

Media access can be both TDMA and CSMA/CA: In the case of TDMA, each Tag is assigned to a timeslot and in regular interval interacts with defined number of Gateways in its physical range (media collisions are avoided so that maximum tag availability is achieved).



Picture5: The Master Gateway acts as a node for the rest of the Gateways.

Each Gateway calculates a distance to particular Tag and sends it wirelessly to the Master. The Master Gateway applies the algorithms to calculate the position, whichever is chosen (TDoA is the choice in complex environments), and it sends to a remote Server via the backhaul (Ethernet). I will cover the usage of this data in the next chapter.

The solution performance is:

- Sub 1-m accuracy (Locates items within 30 cm of where they are 99% of the time)
- Long Range NLoS 30 m, LoS approx. 300 m,
- High-density: can identify up to 11,000 items within a 20m radius.
- Highly reliable, deterministic response time.
- Low power consumption: operates using one order of magnitude less than other solutions. Tags with less than 100nA in sleep mode i.e. typical +3 years' autonomy (600 mAh CR battery, 1s duty cycle).
- Wireless synchronization, no wired synchronization infrastructure required.
- Very high immunity to multipath fading, allowing easy installation.
- Operates in different bands than ISM bands, avoiding interference.
- Optionally, integration of MEM sensors in tags for better accuracy and enhanced performance.

In this system I am not including ATEX directives compliance (long process involved) or the testing of potential RF interference by Arc welding devices and X-ray crack detection gear.

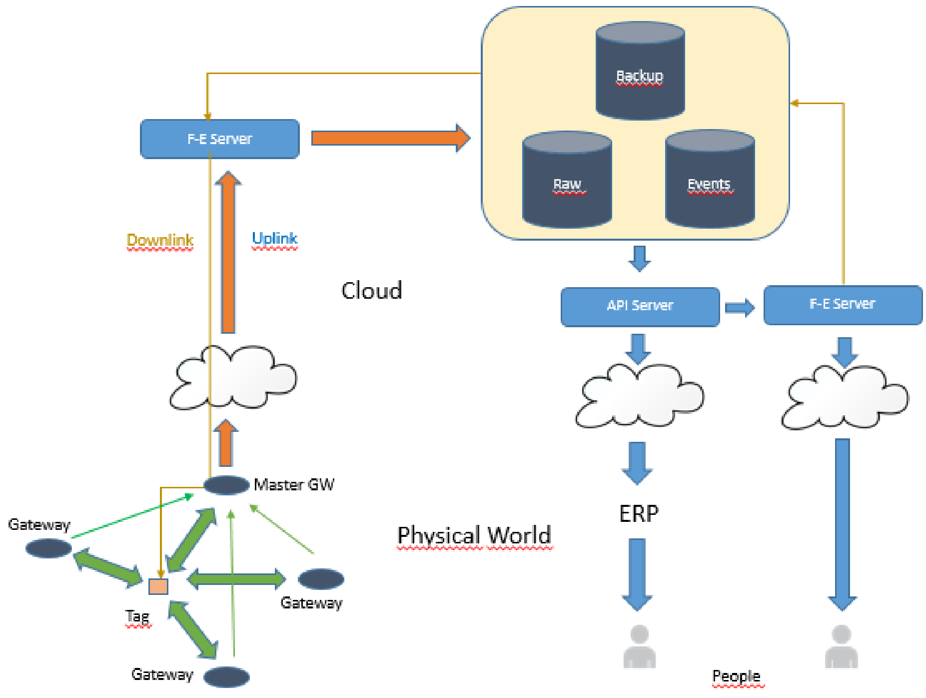
4. System architecture and proposed implementations in real world use cases

This chapter will have two parts. In the first part I will describe the system architecture and elements developed to deploy a complete RTLS solution based on UWB. In the second I will consider two real world cases, one in an automotive factory and the other in a melt shop, and its proposed technological solutions, to be deployed in the near future.

A. System architecture and setup

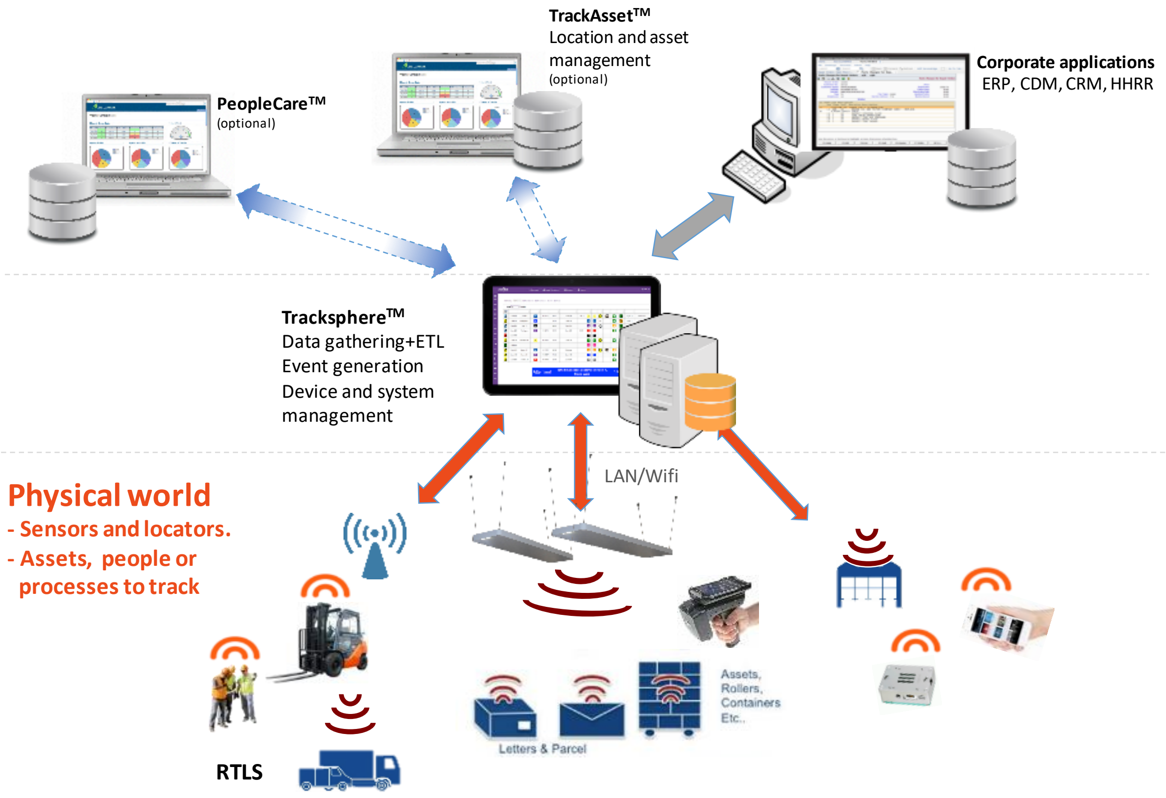
The UWB subsystem generates the raw data of the time of flight readings or TDoA readings. We need to be able to transform and store this information in computing systems to make it usable. The full System is composed of:

- the UWB network (the devices that we saw in the previous chapter)
- connection to the backhaul
- a server to perform an ETL with the received data
- the processes that generate events and apply business rules
- usage of the data (1) via the API to a third party software (WMS, ERP,…) or (2) a Front End Dashboard.



Picture 6: Full solution diagram. In green UWB portion of the solution.

This software, that I co-developed with my partners, is called Tracksphere, and has the functions described in the picture attached. It is a middleware that can gather data from the RTLS tags and also from any IoT sensor or reader (such as barcodes or RFID) from different technologies applying end to end encryption and transactional messaging.

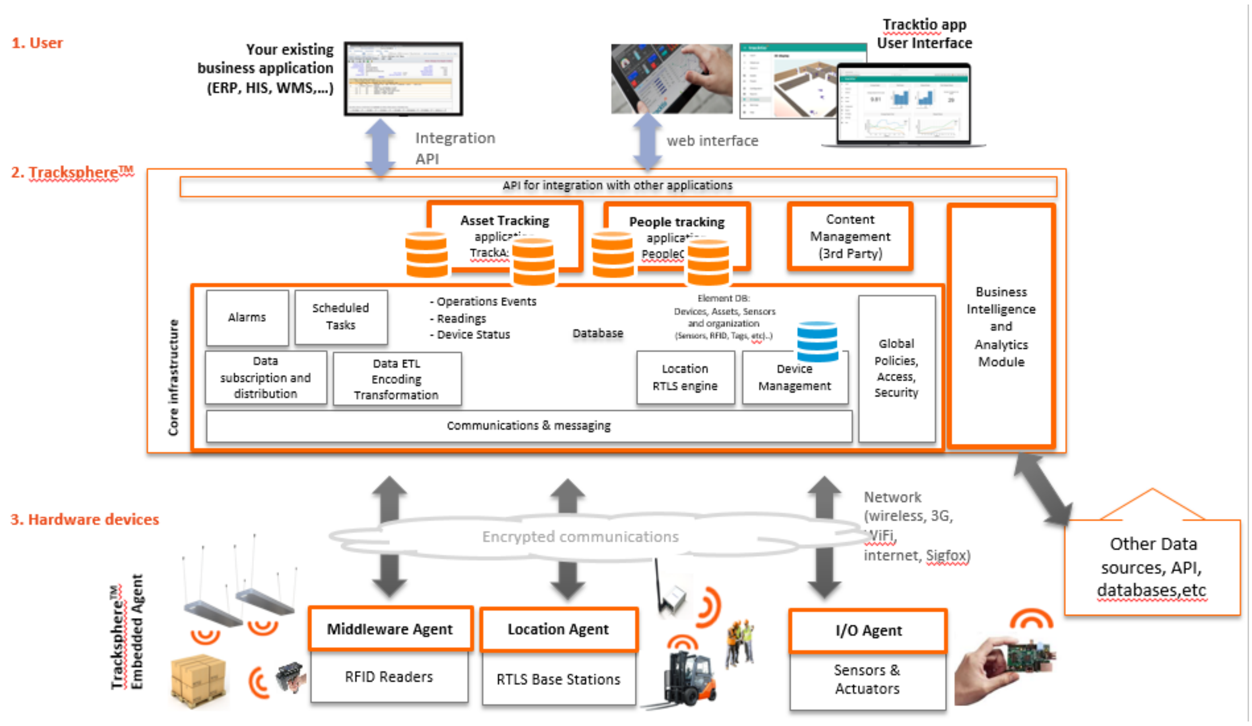


Picture 7: Function of the Tracksphere middleware

TrackSphere is a simple and efficient middleware and database engine that provides:

- Multi-source data gathering, aggregation, and enrichment.
- Technology- and application- agnostic layer between technology-specific layers and other application specific software.
- Provides several common services e.g. device management, format conversion, secure and transaction-oriented messaging, event and alarm management, etc.
- Provides interfaces with (push-pull, sync) and distributes data to any application that needs it.
- Sensor plug-ins, e.g. RFID, RTLS subsystems, and other type of sensors.
- Application-specific software, e.g. asset management–related functions:

- TrackAsset, PeopleCare or any other connected to the interfaces provided

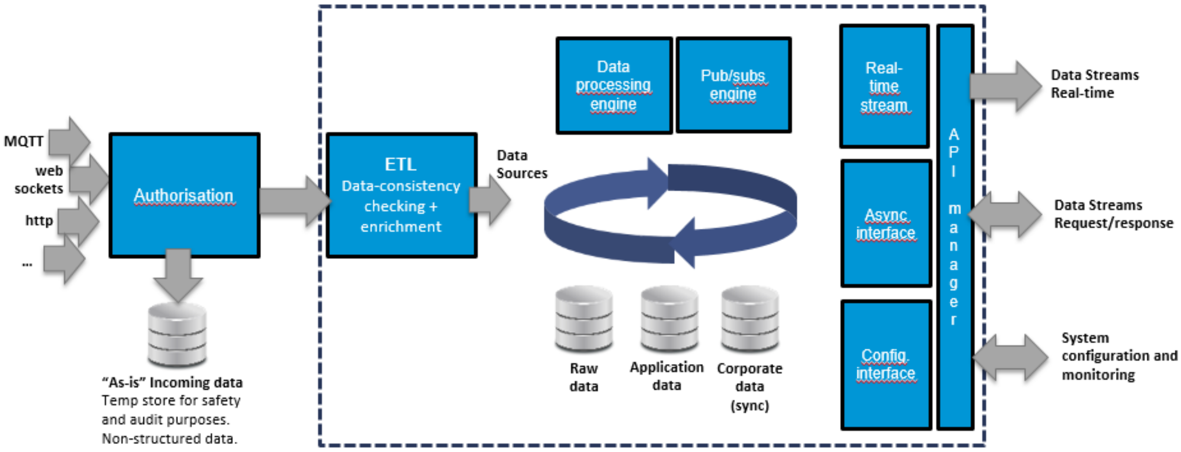


Picture 8: Global Architecture in more detail.

TrackSphere runs from the cloud adapting to the volume needs, in the case of Front End Servers and API servers in Amazon Web Services (AWS) we may use from a single EC2 to multiple EC2 in AutoScaling Groups (ASG) balanced with Elastic Cloud Balancing (ELB). As for the Databases used, it also depends on the volume, there are many options (from PostgreSQL, RDS/Aurora to DynamoDB, MongoDB, Kinesis,..).

The integration with third party applications is key for the real world usage, so it is crucial to have a very advanced API from which data can be obtained real-time or asynchronously. The API is used for three purposes:

- System configuration and monitoring
- Receive Real-Time data streams
- Request Asynchronous Data



Picture 9: Data intake and API detail

Some recommendations for the infrastructure Setup:

- Avoid obstacles between Gateways
- UWB antenna directing downwards or upwards depending the covered area
- Maximum range between Master and Anchor is around 20 to 30 meter for common indoor building conditions and approx. 200 meter outdoor. Use horn antenna for long range capabilities.
- Antenna is not closely surrounded by metal objects (>1cm, preferable few cm or more)
- For better Z-axis measurement place Anchors at different heights or use the special angle of arrival type of anchor.
- The UWB signal usually gets across one or more office type of walls. Maximum 1 to 2 stone walls and max one concrete floor of less the 150mm.
- Keep Line of Sight (LoS) between Master, Gateways and Tags as much as possible for best performance.

B. Sample usage proposals:

In this chapter I will describe two typical scenarios, one in an indoor manufacturing plant, and the second in an outdoor warehouse. After those two real case scenarios, I will address other type of problems in typical industrial scenarios (corridors and production lines, overhead cranes and multi-floor environments with ramps, elevators or cranes) in which UWB RTLS can be of use, and pose possible approaches to solve them.

A. Tow vehicle location in automotive industry

i) Description

This use case is an Automotive part manufacturer. This manufacturer has several plants with manual and robotized processes. Parts travel between those processes in human driven small tow vehicles (similar to carts). We can see the scenario and trains in pictures 10 and 11.

Picture10: Automotive parts tow vehicle

Picture 11: General view of plant (stages and machinery)

One of the many ways to lower the costs of manufacturing is to maximize usage of the different machines. Whatever happens between one process and the next is key to maximizing this usage. Any percentage of improvement in the segments of production chain may improve sensibly the capacity of the plant. The management has the certainty that this process can be optimized by daily observation of the transportation process, but needs real measures of the processes to take informed decisions. So, the first goal that this manufacturer wants to accomplish is to measure the occurrences from the end of a process of the production chain to the beginning of the next one.

The objective is tracking and monitoring of delivery tow vehicles in fixed paths inside a manufacturing facility. There are four routes that are covered by four delivery tow vehicles indoor of this manufacturing facility, and the routes could change in the future. As of today, each route is covered by one delivery tow vehicle. The area of the complete facility has the following dimensions: Length: 185m, Width: 85m, Height: 8-10meters. The initial stage of the project is to track and monitor one route and one tow vehicle for a service coverage area of 2.000 square meters (50m x 40m).

The data that management would like to collect to achieve this objective is:

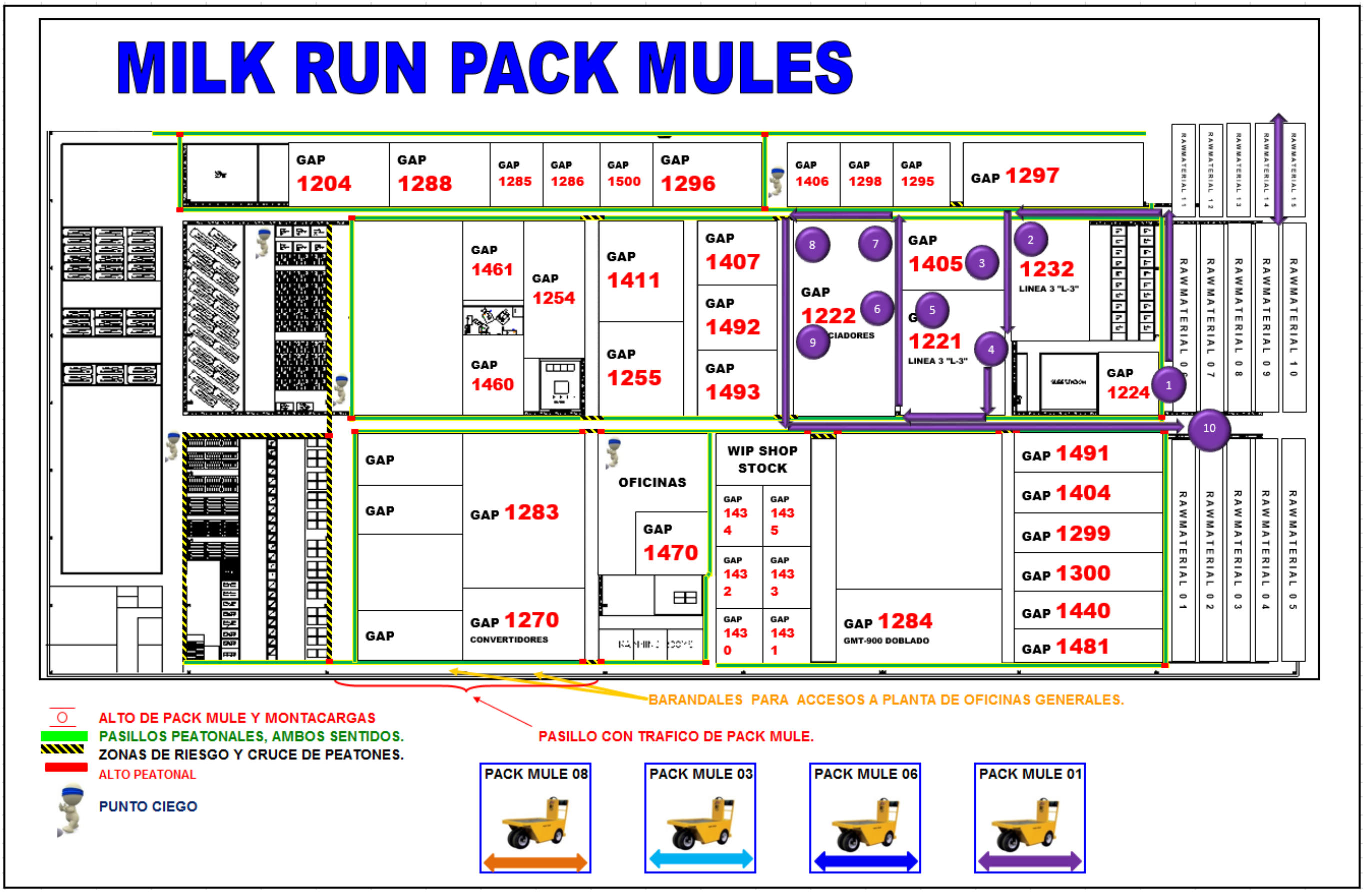
1. Log detailed timing for each delivery tow vehicle and for its each delivery turn including: turn's start time, fixed delivery stop points' timing, non-scheduled

stops' timing and end of delivery turn's timing. Total turns elapsed time, average turn time, total and average stop time on fixed points for each path and delivery tow vehicle.

2. Be able to monitor each of the 4 delivery tow vehicles run their fixed delivery path. Paths have from 7 to 10 delivery fixed stop points. See route B to be considered in phase I of project in Picture 12.

3. A tracking and monitoring application should show in a big screen the current location of each tow vehicle and their currently covered path of the turn in the manufacturing site layout. Also must be shown each tow vehicle: turn elapsed time and remaining time to complete turn (according to turn's average timing for each path).

4. Indoor tow vehicle positioning accuracy required: +/-1m



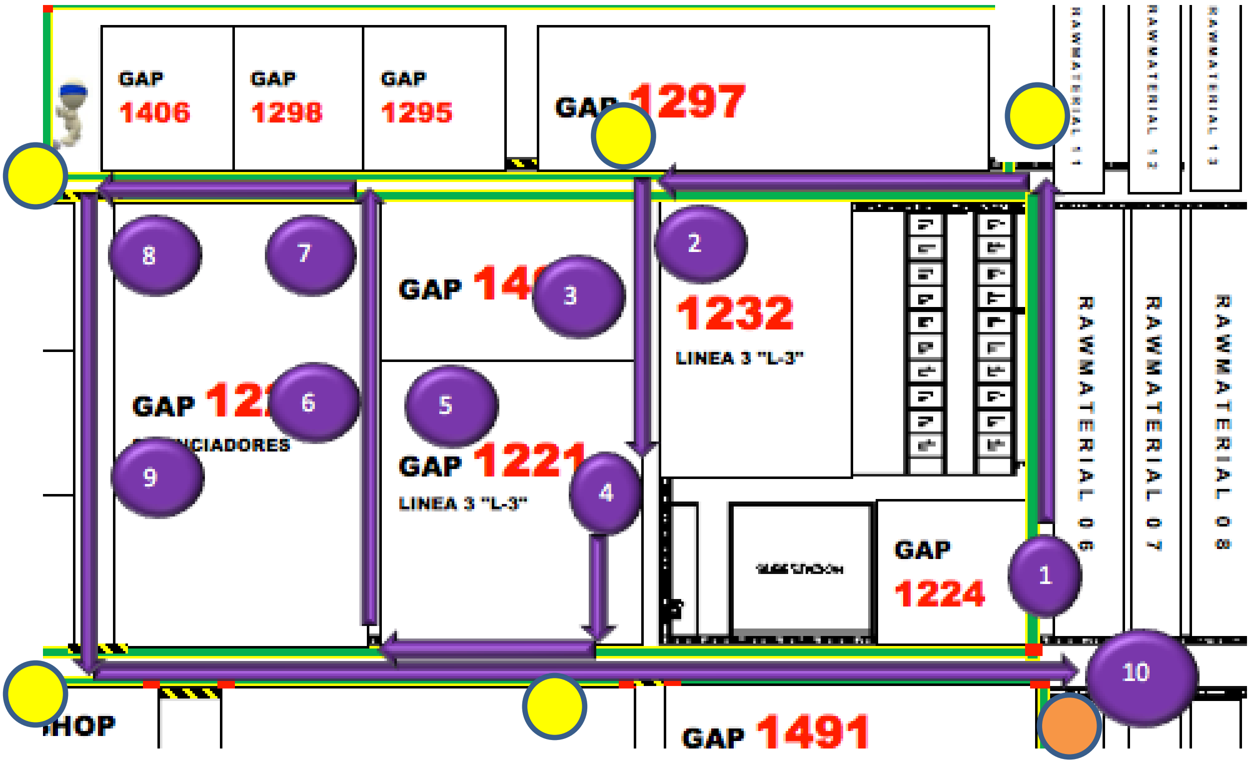
Picture 12: Route B to measure in phase I.

ii)Solution and Deployment design

The objective of this use case is to gather data and allow informed human decision taking based on the information and its graphic display in a dashboard.

As I already mentioned the architecture needed (software platform) I will focus on the UWB portion and the API to the external panel:

- A UWB tag would be placed in the tow vehicle, connected to the battery so that it can be ON continuously and no recharge is necessary
- One master would be placed in the orange dot (where there is Ethernet connection and also the monitor for the manager's dashboard would be placed
- The API would be streaming the position to a web application so that real-time position can be drawn on a map
- Alarms such as vehicle not moving in a certain time could be programmed in Tracksphere
- Events such as timing between positions, time stopped, and so on would be calculated in the post-processing



Picture 13: Route B and suggested gateway (yellow dots) and Master (orange dots) positions.

B. Product and Forklift location in an outdoor warehouse

iii) Description

This second real use case scenario takes place in an outdoor warehouse. The goal is double: staff safety and improve logistics (keep track of goods).

A steel company manufactures intermediate products for many industries, such as construction, white line or any type of vehicle manufacturing. In the process of creating this intermediate products, there is a need for storage of the final intermediate products and also of the materials that are used in the work in progress (for cooling or future use).

Picture 14: Steel coil storage patio

The materials used in steelmaking are very heavy (order of magnitude of tons) and they require very specialized cranes and vehicles to move them from one position to another. The dimension of these materials and vehicles make human activity very dangerous in the surrounding areas, since the force of any seemingly small impact on a person can be deadly.

I am going to focus on an outdoor warehouse (see Picture 14) for the product, in this case steel coils. The position of these coils will be determined by locating the transportation vehicles. See in Picture 15 and 16 the aspect of the product and vehicles. The product's weight is between 2 and 24 tons. Its diameter and depth are between one and two meters.

Picture 15: Steel coil

The transportation vehicles used for steel coil transportation are very heavy duty forklifts that can load up to 24 tons and transport the goods from production to warehouse to different warehouses or load them onto trucks.

Picture 16: Steel coil forklift

The two goals that the management of the plant want to accomplish are:

1) Employee safety: gather moving elements and worker accurate location information to avoid danger whenever a person is standing or wandering near any vehicle or crane.
2) Process improvement: digital accurate location of products would allow a faster picking process for orders and a more efficient design of routes.
3) Real time inventory

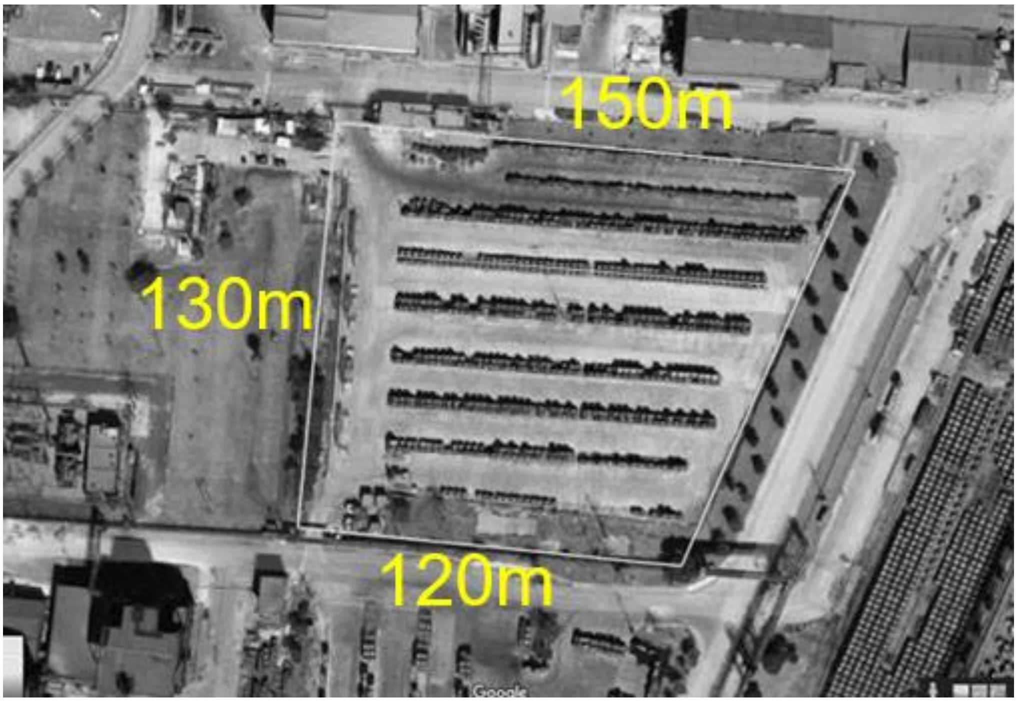
iv) Solution and Deployment design

For this system we will be using RFID and UWB combined:

- RFID tags will be placed on each coil and read every time the forklift is loading/unloading
- The position will be read on the unload event, based on the UWB tag placed on the forklift.

The operator places each coil on an available spot inside the warehouse rather than on a designated spot.

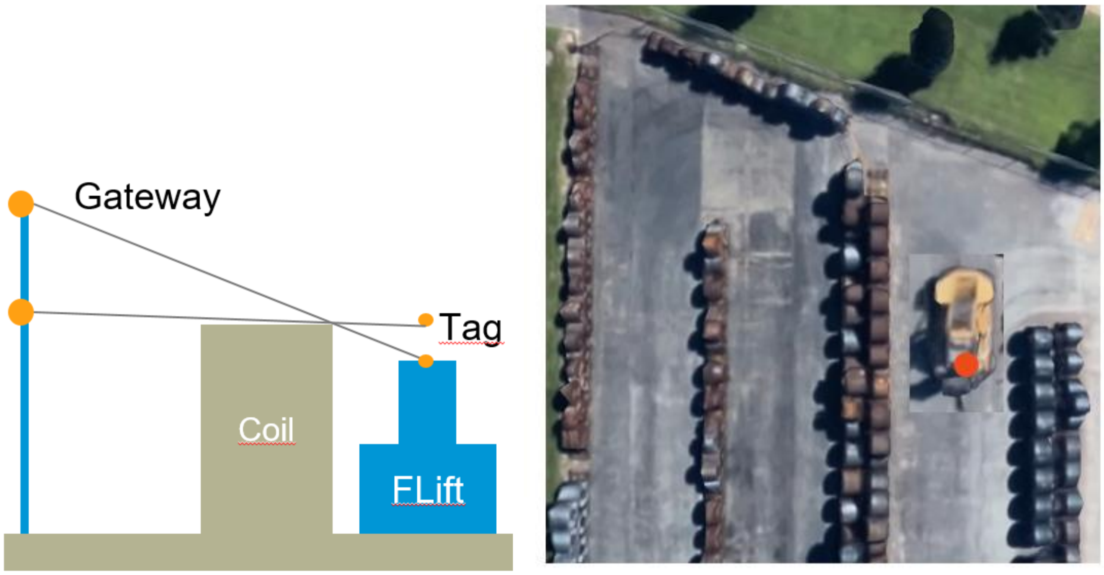
This position is communicated to the warehouse management system via the API and ultimately visualized on a map for the next operator who is picking up the goods. The time wasted in searching for goods is eliminated.



Picture 17: Patio measurements

The size of the corridor is 10m and the forklift's height is above 3m. The height of the corridor is 1.7m, 2.8m and 3.8m depending on the levels of coils stored (up to 3).

In order to ensure the LOS communication between the Gateways and the Forklifts, we will raise the tag if needed by the final position of the tags.



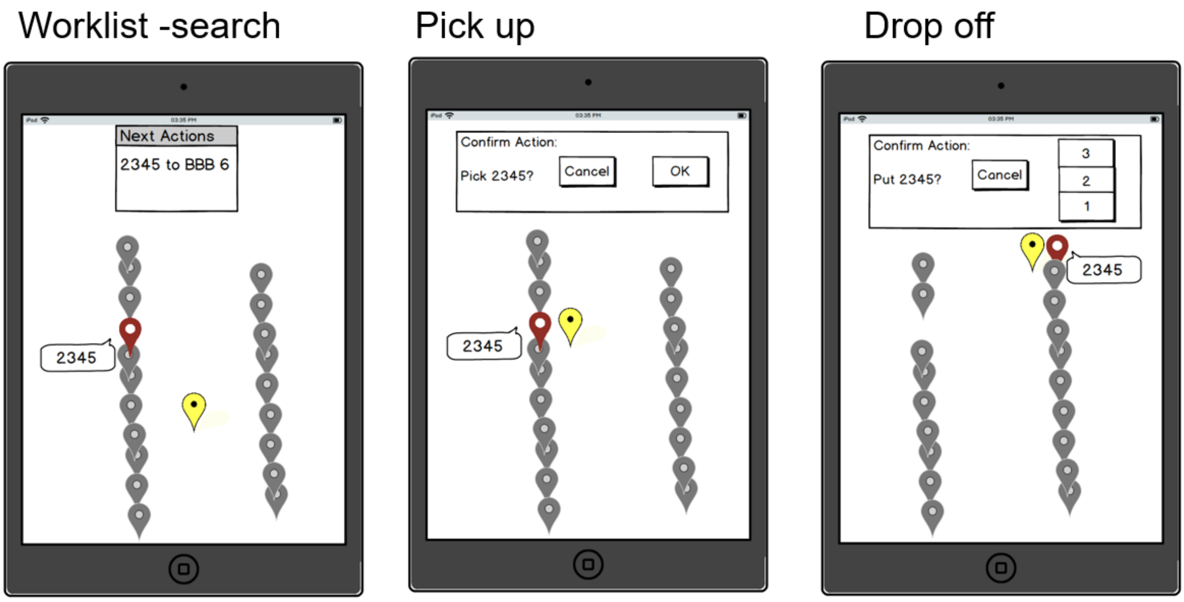
Picture 18: Gateway and tag positions

The position of the tag in the Forklift has to be high enough so that the coil walls do not block the signal.

As for the RFID antenna, it would be placed in front of the forklift, in a protected area, with 4 antennas for diversity and maximize the probability of reading tags in the most difficult positions.

Picture 19: RFID reader and UWB Tag placement.

As for the software part, the WMS would be receiving all the positions of the dropped off coils. The route for a coil shipment could be very easily formed from those positions.



Picture 20: Mockup of the forklift operator’s screen

5. Conclusions

The objectives of the project have been met.

The main objective, designing an architecture needed for the practical deployment and usage of the UWB technology in industrial environments (covered in chapter 3 and 4), has been the most challenging due to the lack of resources for this immature technology.

The requirements in location precision of <50cm, above 99% availability and low lag (under 100ms for real time streams) are successfully met.

As for the secondary objectives:

- I have done an exhaustive comparison between UWB technology and other technologies currently available. All of them have a scenario in which the use could be justified, but it was quite clear UWB provided the most flexibility at this point. (chapter 2)
- I described the solution of a couple real world industrial scenarios in which this technology applies, for international companies that are adopting UWB technology in the next weeks (chapter 4)
- I have gone through the benefits of RTLS in industrial environments (chapter 1 and 2)

From the results of this project it has become clear that UWB is a very valuable tool in positioning for Industrial Environments. I would therefore, advice as future lines to complement and extend the work carried out here improving the accuracy and coverage of the infrastructure by complementing UWB with non-infrastructure techniques such as dead reckoning.

6. Appendix

Appendix I: Abbreviations

The following abbreviations are used in this document:

Definition	Acronyms
Biased Kalman Filtering	BKF
Binary Phase Shift Keying	BPSK
Carrier Sense Multiple Access with Collision Avoidance	CSMA/CA
Channel Impulse Response	CIR
Extended Kalman Filter	EKF
Federal Communications Commission	FCC
Full Function Device	FFD
Global Positioning System	GPS
Global System for Mobile Communications	GSM
Impulse Radio Ultra WideBand	IR-UWB
Indoor Positioning System	IPS
Infrared	IR
Infrared Data Association	IrDA
Joint Committee for Guides in Metrology	JCGM
Location Based Services	LBS
Least Square with Distance Contraction	LS-DC
Line of Sight	LOS
Local Area Network	LAN
Low data Rate UWB	LR-UWB
Maximum Likelihood Estimation	MLE
Micro Electro Mechanical Sensors	MEMS
Minimum-Shift Keying	MSK
Non-Line-of-Sight	NLoS
On-Off Keying	OOK
Pseudo Random	PR
Pulse Amplitude Modulation	PAM
Pulse Position Modulation	PPM
Pulse Width Modulation	PWM
Radio Frequency	RF
Radio-Frequency Identification	RFID
Real-Time Location System	RTLS
Received Signal Strength	RSS
Reduced Function Device	RFD
Strengths, Weaknesses, Opportunities, and Threats	SWOT Time
Difference of Arrival	TDOA

Time Division Multiple Access	TDMA
Time-Hopping Binary Phase Shift Keying	TH-BPSK
Time-Hopping Pulse Position Modulation	TH-PPM
Time-Hopping Spread Spectrum	TH-SS
Time Modulated Ultra WideBand	TM-UWB
Angle of Arrival	AOA
Time of Arrival	TOA
Transmit Power Control	TPC
Ultra WideBand	UWB
Weighted Least Square with Multidimensional Scaling	WLS-MDS
Wireless Fidelity	WiFi
Wireless Local Area Network	WLAN
Wireless Personal Area Network	WPAN
Worldwide Interoperability for Microwave Access	WiMAX

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