Universidade de Aveiro
2018
Departamento de Eletrónica,
Telecomunicações e Informática

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Sistema de localização para um drone autónomo com aplicação em ambientes interiores

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia de Computadores e Telemática, realizada sob a orientação científica do Doutor António José Ribeiro Neves, Professor auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro.

o júri / the jury

presidente / president	Prof. Doutor José Luis Costa Pinto de Azevedo Professor Auxiliar da Universidade de Aveiro
vogais / examiners committee	Prof. Doutor Paulo José Cerqueira Gomes da Costa Professor Auxiliar da Faculdade de Engenharia da Universidade do Porto (arguente)
	Prof. Doutor António José Ribeiro Neves Professor Auxiliar da Universidade de Aveiro (orientador)

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Palavras Chave Localização, drone, robô autónomo, voo, RFID, Marvelmind.

Resumo

Na área da robótica, a capacidade de decisão em prol da avaliação do ambiente envolvente é uma capacidade em constante evolução e sujeita a alterações repentinas, com o objectivo de aproximar o comportamentos dos robôs ao comportamento humano com base em dados sensoriais. Embora esta tarefa seja de elevada complexidade, o desenvolvimento da tecnologia utilizada para tal, tornou possível alcançar cada vez melhores resultados o que contribui para o desenvolvimento de soluções cada vez mais próximas da realidade.

As principais dificuldades sentidas aquando do desenvolvimento de soluções nesta área consistem à mobilidade autônoma em ambientes fechados uma vez que é necessário assegurar a precisão dos sistema de localização utilizados, de forma a possibilitar que robô tenha informação necessária acerca da sua localização relativa e assim agir em concordância com o objectivo e no menor tempo possível.

O processo de investigação e desenvolvimento associado a esta dissertação recai sobre a necessidade de encontrar soluções para a localização em interiores de forma a possibilitar voo autónomo de drones capaz de efectuar o controlo de stock em armazéns que possibilitem o voo do mesmo, uma vez que as características dos ambientes internos impossibilitam o uso do sistemas baseados na posição global ou qualquer outro tipo de localização geográfica devido aos materiais que compõem a sua estrutura.

Assim sendo, do estágio associado a esta dissertação, resultou um sistema de controlo para drones autônomos capazes de efetuar inventário, com recurso à tecnologia de identificação por rádio frequência, baseado no posicionamento interno. Dado ser um processo faseado, diversas soluções foram estudadas em resposta aos problemas e objetivos característicos de cada um dos diferentes módulos, organizados prioritariamente de acordo com sua relevância para o resultado final. Numa última fase do projecto, será desenvolvida uma solução capaz de interligar todos os módulos desenvolvidos para que desta forma seja possível apresentar uma solução que sustente o desenvolvimento futuro de módulos necessário.

Keywords Indoor position, autonomous robots, drone, RFID, Marvelmind.

Abstract

In robotics, the decision capabilities according to the surrounding environment evaluation are under constant evolution, subject to sudden changes, with the aim of merging the behavior of robots and humans based on sensorial data.

Even though it is a complicated task, every year new solutions are built and the complexity of this task has been by-passed enabling better results that contribute to more realistic solutions.

The main difficulties in the solutions developed in this area are related to the independent movement control in indoor spaces once that is necessary the use of precise positioning systems necessary for the correct localization input data to the robots ensuring the best action order as quickly as possible.

The research and development process presented in this thesis is related to the need of finding an appropriate solution for the indoor positioning systems applied to an autonomous drone. However, due to the construction materials of this type of buildings, it is not possible to use systems based on global position systems (GPS).

Therefore, with the conclusion of the trainee program associated with this thesis, the output is a control system for autonomous drones based on the indoor position, capable of making warehouse inventories using Radio Frequency Identification (RFID) technology.

During the development process of a modular system, several solutions were considered in response to the issues and objectives of each module organized taking into account its significance for the final product. In the last project phase, it was developed a control module to support the integration of each part and also allowing the inclusion of necessary future modules.

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Glossary

ROS	Robot Operating System
MAVLink	Micro Air Vehicle Link
UAV	Unmanned aerial vehicle
GB	Giga Byte
RAM	Random Access Memory
PWM	Pulse With Modulation
PPM	Pulse Position Modulation
PCM	Pulse Code Modulation
DJI	Dà-Jiāng Innovations Science and Technology Co., Ltd
DC	Direct current
BLDC	Brushless DC
Kv	Motor velocity constant
V	Volt
A	Ampere
LiPo	Lithium Polymer
KHz	Kilohertz
MHz	Megahertz
GHz	Gigahertz
cm	centimeter
RPM	Rotations per minute
ESC	Electronic speed controller
OS	Operating System
IPS	Indoor Position System
GPS	Global Positioning System
USDOD	United States Department Of Defense
OCS	Operational Control Segment
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
RFID	Radio frequency identification
UHF	Ultra High Frequency
LF	Low Frequency
HF	High Frequency
SHF	Super High Frequency
RSS	Received Signal Strength
TOA	Time Of Arrival
TDOA	Time difference of arrival
RTOF	Round-Trip Time-Of-Flight
POA	Phase of Arrival
AOA	Angle of Arrival
IMU	Inertial measurement unit
PID	Proportional Integral Derivative
I2C	Inter-Integrated Circuit
USB	Universal Serial Bus
TDMA	Time Division Multiple Access
US	United States
3D	3 dimensions
SMA	SubMiniature version A

CHAPTER 1

Introduction

A few years ago, with the necessity of control and monitoring conflict zones, the US military forces were forced to develop aerial mechanisms to ensure the safety of their pilots and given this necessity, the concept of Unmanned aerial vehicle (UAV) appeared. A few years later, it has been concluded that this type of vehicles could be a helpful tool in some tasks reducing the risks and the time to the user improving the efficiency of the assignment. With this conclusion, many drone manufacturers arise in response to the demand for the most diverse objectives.

This dissertation is the result of a new purpose for commercial drones facilitating the inventory process in warehouses using auxiliary RFID technology to detect and identify all different products available in real time as shown in Figure 1.1.

Based on well-known drone frame where they were added many auxiliar modules as the Indoor Position System (IPS), the radio frequency reading modules, the central control unit called autopilot, among others. Even existing some proposed solutions in the retail community, there is no final product available in the market with the required characteristics, but there are many separate modules that can be used to obtain good results although in some cases its cost is very high and not suitable for proof of concept.

Throughout this document, we will discuss several commercial solutions for the current difficulties although sometimes these are discarded given the financial constraints of the project or incompatibilities.

After the research and development of the solution, it was possible to ensure the efficient operation of a system capable of managing the inventory and positioning modules and supporting the future integration with a commercial drone and also with collision avoidance system.

Figure 1.1: Application scenario for the use of the developed system.

1.1 Motivation

With technological advances of the last years, the industry has been increasing the research for new solutions to improve the efficiency of their production processes. The retail industry is one of the most exciting entities in solutions capable of increasing efficiency, reducing time spent in the inventory process in warehouses with dimensions that justify the use of automatic mechanisms of stock management.

The main reason for the interest for this type of solutions is related to the tracking incapacity between reception and dispatch products management phases which leads, in some cases, to the product losses.

Typically, the existent solutions need a worker for each terminal as it happens with the barcode or even with RFID mechanisms. This processes associated with reading difficulties in some places lead to an increase in the time needed to the process and consequently higher costs. Therefore, given this necessity, the company Tyco Retail Solutions, a specialist in stock control solution, propose this dissertation as an investigation project to evaluate different possibilities to improve existent solutions.

1.2 Objectives

The primary objective of this thesis is the development of a complete system capable of improving read rates, reducing time spent and necessary labor force and consequently the costs, to apply in large warehouses where the inventory process requires many workers and a lot of time. In response to this challenge, the development process must be separated into different phases presented below.

1. **Bibliographical research:** Research about the actual state of the art of each module and existent solutions such as the different classes of unmanned aerial vehicles, their components and control technologies and also indoor and outdoor positioning mechanisms and existent indoor systems.
2. **Setup construction:** Selection of drone components and assembly.
3. **RFID system integration:** Construction of a low weight RFID system and assembly in the drone structure.
4. **Indoor Positioning system:** Integration of IPS in drone structure.
5. **Autonomous flight:** Autonomous flight algorithm development.
6. **Integration tests:** Test the performance of all modules and their integration on the system.

1.3 Structure of the dissertation

This thesis is divided into seven other chapters beyond the introduction chapter.

The second chapter, called State of the Art, present the research related to the existent mechanisms and technologies used during the project.

The Case Study chapter aims to present the problem and solutions explored in this dissertation and also the relationship with the company development field.

The first practical chapter, called Drone, describes the structure of the drone and the hardware and software created to support the development.

Indoor Positioning chapter presents the Indoor positioning system selected, configurations, their integration into the system and limitations.

In Autonomous flight chapter, it will present the central algorithm developed to control the drone based on all secondary modules.

In Results chapter, it will present the results of each phase and their influence on the final solution.

Finally, in the last chapter, it will be presented the global conclusions about the entire project, difficulties and future works.

CHAPTER 2

State of the Art

This chapter supports a brief description of necessary prior research for each main topic approached in the present dissertation. This previous study about the main areas covered by this work makes possible the choice of technologies and components used for each stage but respecting the imposed constraints of the project. Some considerations about the history and the application areas of each main components are exposed as well as the different solutions that can be implemented with similar systems or parts of them.

Three different parts constitute this chapter. In the first, some historical facts about UAV's are presented as well as the several types of existent vehicles and their main components. The last section is intended for the presentation of the principal active positioning method used in outdoor and indoor scenarios.

2.1 Unmanned aerial vehicles

The public perception of most of the UAV applications is still mainly associated with military use, but many seem to forget that one of the founding fathers of the idea of remotely controlled vehicles was the genial civil inventor - Nicola Tesla. In fact, Tesla published the first patent [1] related to remote-control for unmanned vehicles described as 'teleautomation', becoming one of the main knowledge bases for today's UAV's.

The investigation in this area for military purposes dates back to the end of the 19th century. The massive investigation was triggered by the Military leaders need of reaching their enemies from a distance with the objective of avoiding human casualties. As its expected, the US military sector was the first to apply the idea of military aerial surveillance, during the Civil war. However, other countries also followed the same steps. Even if the emergence of such vehicles is associated with military purposes, nowadays they are classified in many types and sub-types being its type associated with the physical characteristics and use.

As the technology becomes more advanced and costs fall, day-to-day civilian uses of UAVs are developing rapidly and at the same time, military drone activity has caused public outcry given their primary objective. However, when speaking about UAV's dedicated for civil use, it is essential to distinguish between the large, civilian vehicles that might one day carry passengers without onboard human supervision, regular UAV's of similar size as those used in the military and much smaller systems, including increasingly popular copters.

Their size and portability become an appealing feature for agriculture, police forces, rescue missions, topographic monitoring [2] and fire services, as shown in Figure 2.1, to study whether their adoption might be feasible for their aerial surveillance purposes [3].

Figure 2.1: Drones for autonomous search and rescue [4].

On the other hand, the use of small UAV'ss by other than regulated entities raises questions of privacy and physical safety once that, without any association between de UAVs, and their flight operators or owners, examples of irresponsible and discreet use are not discarded. In 2017, many cases of UAVs violating the restricted area of airports are reported once that with their current characteristics can achieve sufficient altitudes that compromise the safety of commercial and non-commercial flights. With these occurrences, the creation of legislation to control the freedom of users such as vehicle registration, limitation of flight areas and many others, was mandatory. Once that these regulations are created exclusively for outdoor flight in public areas being the UAVs used for indoor purposes that operate in private buildings are not covered by this rules.

On another hand, one of the leading causes of the increased demand and utilization of this type of small vehicles is the personal projects. With the emergence of high power density batteries, long range and low-power micro radio devices, cheap airframes, powerful microprocessors and motors, UAVs have become applicable in civilian circumstances such as remote sensing, mapping, traffic monitoring and image capture, tasks that until now, without small UAV's or copters and their characteristics, are almost impossible or costly. This event has led manufacturers to ensure the progressive development and production in response to the market demand. Since this dissertation is related to small UAV's to operate in indoor spaces, the contents present in the remaining document are applicable to small drones although they can also be used for other types. In the following subsections, a brief description of the main constituent parts and the operating method are presented in order to clarify some technical aspects.

2.1.1 Flight control

Being a subtype of airplane, UAVs movements have three degrees of freedom performing rotations around three axis (x, y, z) from the plane's center of gravity. The position control of UAV is usually converted to the angular control decomposed on roll (ϕ), pitch (θ) and yaw (ψ), as shown in Figure 2.2.

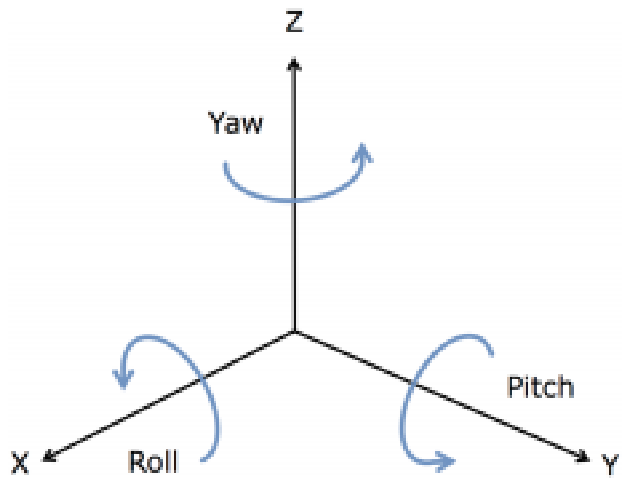


Figure 2.2: Angular rotation axes [5].

This is the standard motion variables for drones controlled by radio or controlled by any other system. In this dissertation, both control methods are explored. In the first approach, the drone is controlled by the radio system to test and prove the reading rate efficiency, and in the second approach, this was replaced by the autonomous flight algorithm that emulates the reception of angular control variables based on indoor positioning system and other input signals.

Radio controlled small UAV's are also called RC planes, which are usually controlled by an RC hobbyist through a hand-held RC transmitter with an RC receiver incorporated on drone structure. The signals transmitted can be Pulse Position Modulation (PPM) signals, or Pulse Code Modulation (PCM) signals, operating in different frequencies depending on the country in which they are used. The frequency is usually fixed for RC transmitter/receiver and up to eight channels of PPM signals can be transmitted each time depending on the number of different operation that can be sent from RC controller to the receiver. After the receiver decodes the signals from the transmitter, pulse width modulation (PWM) signals will be generated and processed to serve as input signals for the Electronic speed controller (ESC) and consequently to each motor. These type of controllers are considered as an electronic circuit that has two primary functions. First, to regulate the battery source down to the voltage needed by motors. Second, to convert the motion signals in brushless motor control output.

On the other hand, autopilots were firstly developed for missiles and later extended to aircraft and ships, differ from the previous control mode because in this case, there is no human interaction with the vehicle. However, in order to enable the flight control in real time, autopilot systems include external sensors and onboard processors to perform movements decisions according to the analysis oh the surrounding environment. Due to the high nonlinearities of the airplane dynamics, a lot of advanced control techniques, such as Proportional Integral Derivative (PID) controllers and positioning systems, have been used in autopilot systems to ensure smooth desirable trajectory navigation. PID is a control loop feedback mechanism which calculates the error e(t) continuously as the difference between the desired setpoint r(t) and a measured process variable y(t) and applies the correction based on proportional (Kp), integral (Ki) and derivative (Kd) terms.

$$u(t) = kp \times e(t) + ki \times \int_0^t e(\tau)d\tau + kd \times \frac{de(t)}{dt} \tag{2.1}$$

These control systems are common to both types of the operation mode of the small UAVs. However, in the autonomous autopilot system, the input signals to control its movement comes from an algorithm that operates according to the positioning system information, the coordinates of the intended route, and in some cases, based on collision avoidance system outputs. The positioning system is mandatory in this type of flight modes being composed of GPS-based navigation systems or indoor positioning systems given that the GPS systems do not operate correctly in indoor spaces. The next section presents some considerations about the different existing algorithms and techniques of navigation and positioning systems with particular incidence on indoor systems.

2.2 Navigation and positioning systems

During the last two decades, significant developments have taken place in navigation and positioning techniques. These have occurred not only in classical radio and acoustic methods but also in satellite and inertial technologies even that Radio navigation is still the most commonly used surface navigation and positioning method. The emergence of different techniques for the same objective is caused by the difference of ranges and accuracies obtained with each method.

The most well-known outdoor positioning system, the Global Positioning System (GPS), is a satellite-based navigation system made up of at least 32 satellites, capable of almost instantaneous positioning to an accuracy between 10 and 20 meters, with higher accuracies obtainable from observations over a more extended interval. Initially used by the United States Department Of Defense (USDOD) for military use, they were made available for civilian use in the 1980s [6]. Nowadays, the current Operational Control Segment (OCS) includes a master control station, an alternate master control station, 11 command and control antennas, and 16 monitoring sites [7] as shown in Figure 2.3.

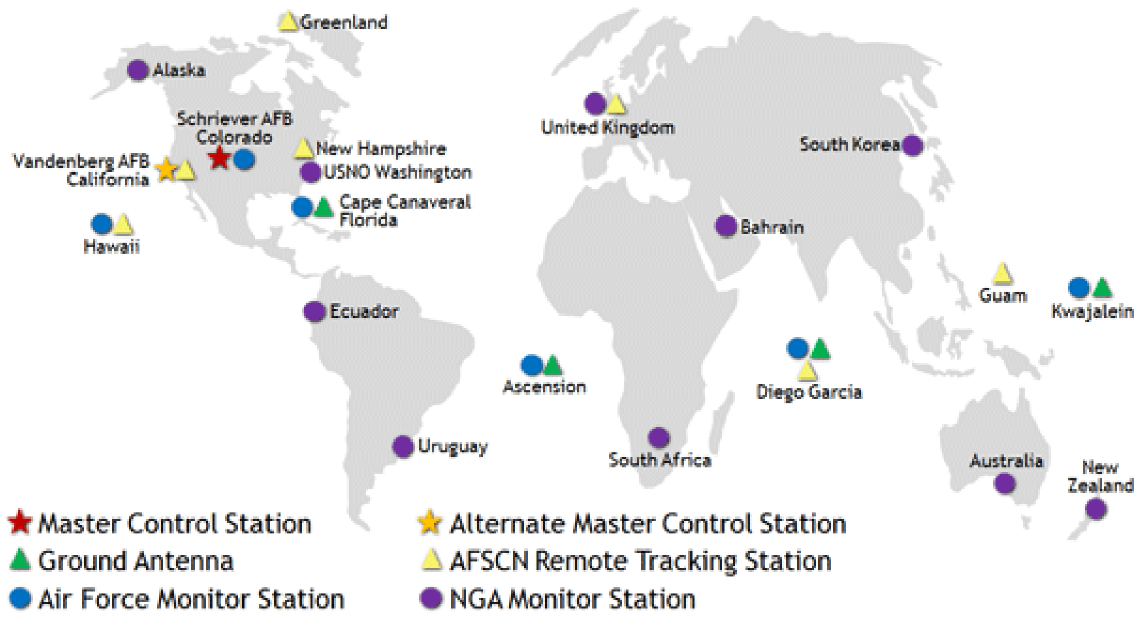


Figure 2.3: Worldwide GPS control segments [8].

This system works based on a principle that satellites circle the earth twice a day in a precise orbit. Each satellite transmits a unique signal and orbital parameters that allow GPS devices to decode and compute the accurate location of the satellite. GPS receivers use this information and trilateration to calculate a user's exact location. In theory, this is done by measuring the arrival time of the signal from the GPS satellite. This signal carries timing information from the atomic clock onboard the satellite and the measured time delay thus indicates the distance. Depending on the number of different satellites signals, GPS receiver can calculate two dimensions (latitude and longitude positions if at least three satellites communicate with the receiver or three dimension positions (latitude, longitude and altitude) if it is possible to receive the signal of 4 or more satellites. GPS receivers will track 8 or more satellites depending on the time of day and where you are on the earth.

Beyond GPS, there are many other types of positioning systems as well as algorithms used in this system. However, the navigation and positioning systems can be distinguished by the operation area as indoor or outdoor systems. Unlike GPS that operates in outdoor areas, there are systems designed to use in indoor spaces.

As suggested by the previous exposition, there are a large variety of positioning techniques and positioning systems. However, there is only a limited number of algorithms and methods to infer location information from measurements. A central problem of understanding location is that this inference is usually based on a set of measures of physical sizes and these measurements contain generally a considerable amount of noise or even systematic errors of measurement.

The rest of this section introduces some basic algorithms of location determination, applicable in indoor and outdoor areas in the same manner even that the investigation made for this dissertation focus on the indoor positioning systems.

In this particular case (inside buildings) it is often difficult to estimate the distance between two fixed points due to multipath effects. When trying to measure the distance between two points which are not in a line of sight, one estimates the length of the transmission path, which can be quite different from the distance between the two points.

The following subsection presents a brief description of the main positioning techniques.

2.2.1 Lateration

Lateration estimates an absolute or relative position of an object by measurement of distances from multiple reference points, as illustrated in Figure 2.4 [9]. This distance estimation method needs at least three fixed reference points to determine the position.

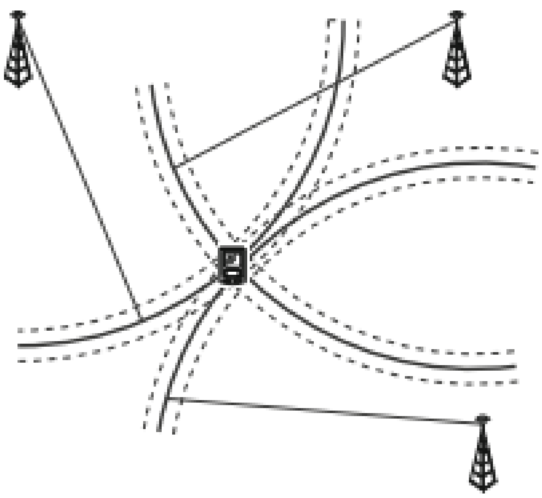


Figure 2.4: Graphical representation of the lateration method [9].

Therefore, the lateration approaches often lead to imprecise results unless they are under in line-of-sight conditions. These distances can be provided by such signal measurement information as a Received Signal Strength (RSS), the phase based mechanisms [10] like Phase of Arrival (POA) or by timing measurement [11].

For the timing approach, we consider three general classes depending on which time to measure, namely:

- Time Of Arrival (TOA): The absolute point in time at which some signal (e.g., light, sound, radio) set out at some known place and time reaches the mobile device can be measured.
- Time difference of arrival (TDOA): The mobile device can measure the time difference between two signals sent out from different places at the same time.
- Round-Trip Time-Of-Flight (RTOF): The time difference between sending out a signal and receiving a reflection of the same signal is measured.

A pure mathematical expression to traduce the distance measured error in this type of system can be represented by $c \times t$, in which c represents the propagation velocity of the signal and t the clock error at the mobile device.

Applying this formula to practical cases with a different type of signals and consequently different propagation velocities and assuming that the clock error at the mobile device is 1 μs.

Assuming that the system uses radio communication for positioning with the propagation speed of 3×10^8 m/s, this time error introduces a length estimation expressed by the Equation 2.2 [9].

$$Error = (3 \times 10^8)m/s \times (1 \times 10^{-6})s = 300m \tag{2.2}$$

However, using audio signals such as ultrasonics, as the system chosen in this dissertation, with the same type of approach and the same conditions as in the previous example leads to a much better localization estimation due to the slow propagation speed of sound of approximately 343 m/s (Equation 2.3 [9]).

$$Error = 343m/s \times (1 \times 10^{-6})s = 3.43 \times 10^{-3}m \tag{2.3}$$

In resume, depending on the signal type used in each different application, the propagation error in case of not precise synchronization of the mobile devices the resultant error can be tolerated or not, depending on the accuracy required.

Another variant of alteration techniques is Hyperbolic lateration in which the measurement input does not consist of distance calculations to known locations but approximations of distance difference. In this case, the infrastructure must be well synchronized producing events at the same time, which can be received at different times by a mobile station thereby using TDOA method. The most important advantage of this measurement of time differences is that the mobile device does not need to be time synchronized with the sender of a signal. When the difference of the mobile device from two base stations is known, then the mobile entity resides on the hyperbole defined by this distance difference as presented in Figure 2.5.

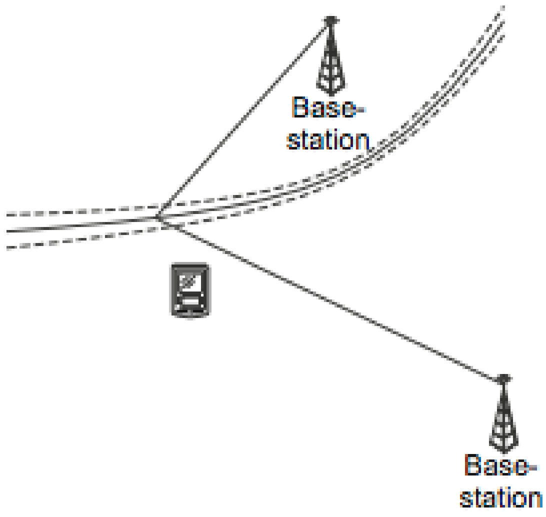


Figure 2.5: Graphical representation of hyperbolic lateration method [9].

2.2.2 Angulation

Angulation method is another very common class of positioning approaches based on the Angle of Arrival (AOA) in which measured angles between known base stations and mobile devices are used to infer the location of the mobile device. For angulation method, there are two general perspectives regarding angles: either the angle between fixed points and mobile devices is measured at those fixed locations or the mobile device measures angles concerning the incoming signals of base stations [9]. In this case, time synchronization process between all system entities is not required as opposed to some of the lateration algorithms. However, complex hardware requirements and sensitivity of AOA algorithms to many different factors are the significant disadvantages of angulation algorithms, illustrated in Figure 2.6.

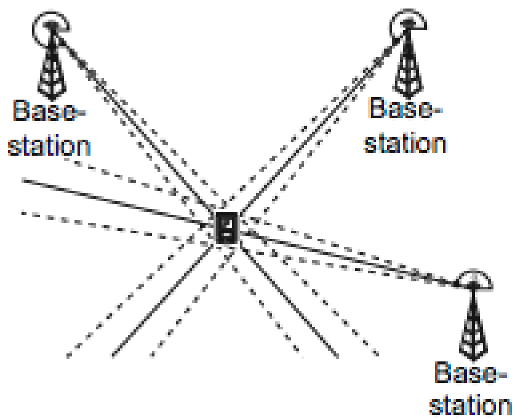


Figure 2.6: Graphical representation of angulation method [9].

2.2.3 Proximity Detection

Proximity detection is a class of location determination algorithms which are based on the proximity of the mobile device to well-known locations. These methods can be applied to Wi-Fi network, once that the proximity to the access point as the Wi-Fi signal is limited to a region around the access point and proximity detection does not provide location in the form of coordinates but preferably in kind of sets of possible areas of the user to a large and complex region.

Therefore, a matching process between all access points, for example, is required to intersect these sets and reduce the regions of possible residence of the mobile device. In a simplified way, the range of a wireless infrastructure would be well represented by a circle with a specific radius. Them, using much Wi-Fi access points the location of mobile devices can be predicted as the intersection of the different circles that represent each access point range as shown in the Figure 2.7.

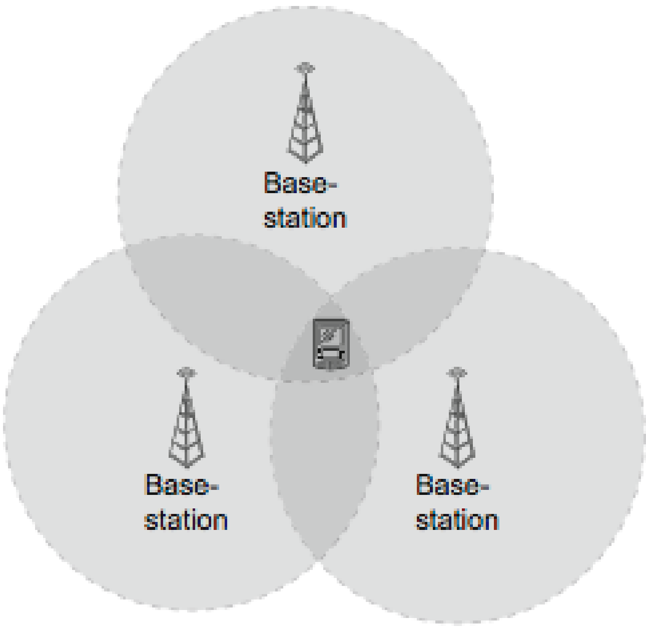


Figure 2.7: Graphical representation of proximity detection method [9].

2.2.4 Inertial Navigation

Inertial navigation systems are based on estimating the location of the mobile device using only measurements made inside the motion unit. It is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position, orientation and velocity of an object relative to the well-known starting conditions.

A Inertial measurement unit (IMU) typically is composed of six elementary sensors measuring acceleration in three pairwise orthogonal directions and three gyroscopes each measuring rotation around one axis, illustrated in Figure 2.8.

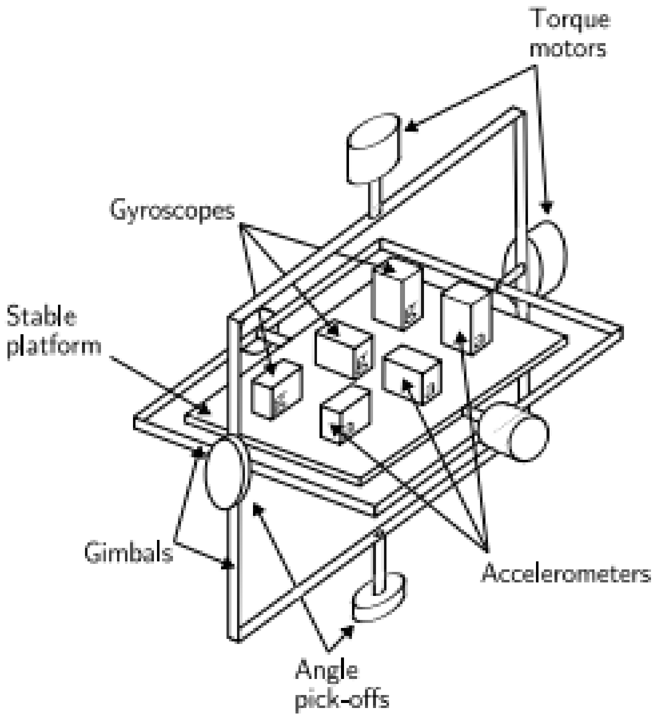


Figure 2.8: Representation of an inertial measurement unit [12].

The most important advantage of inertial navigation lies in the fact that the mobile device can operate completely autonomous does not depend on any infrastructure. On the other side, the greatest drawback of inertial navigation is that the location of a device cannot be observed directly from within the inertial frame of the mobile device. Hence, measurement errors in sensor data will accumulate over time rendering making them useless after a specific amount of time depending on the accuracy required [12].

2.2.5 Fingerprinting

Location fingerprinting techniques typically using existing Wireless Local Area Network (WLAN) infrastructure have been suggested for indoor areas where the GPS does not work well. This technique can be divided into two stages. The first phase consists in the creation of an RSS pattern for each virtual cell grid, in order to create a database or a table of predetermined RSS values related to each point of the grid called point location fingerprint [13].

In the last stage, the mobile station will report a sample measured vector of RSS from different stationary stations to a central server. The server uses an comparation method to estimate the location of the mobile station and subsequent sharing of information with the same.

The most common algorithm to estimate the location computes the Euclidean distance between the measured RSS vector and each fingerprint in the database. In the end, the estimated position is the location that presents smallest Euclidean distance. For another words, this algorithm is based on successive RSS comparison with the patterns acquired in the initial stage.

One of the disadvantages of this method is that with the more complex an environment and the behavior of underlying physics become the more difficult can the physical laws be used to infer the location. However, these complexities make data locally unique and distinguishable leading to a new technique of location determination known as fingerprinting.

2.3 Indoor positioning systems

Indoor positioning is the process of determining the location of a mobile device inside buildings. These type of positioning systems are much more complicated than the global positioning systems taking into consideration the diversity of application areas and their distinctive characteristics.

Over the years, many additional algorithms must be developed to provide accuracy below 1 meter of expected error that is not even available outside buildings. Indoor positioning is for different application scenarios and should, hence, not be discussed isolated from a concrete application because the most crucial trade-off before choosing an indoor positioning system is between cost and accuracy.

However, the application is not at all interested in the position in the sense of location coordinates but much more into the fact of being near to some point. It can be a good idea in such cases to distribute digital beacons at these places, for example, based on Wi-Fi, Bluetooth, audio or Radio-Frequency Identification (RFID) technology. The following subsection collects several typical indoor positioning systems for each of the previously explained approaches.

2.3.1 Light-Based systems

The light-based positioning techniques for indoor spaces are based on the reflection properties of the light [9].

The most prevalent systems use RTOF approach together with the physical reflection of modulated light waves even that modulation is only used to distinguish between scattered light and the reflection.

A very common example of the application of this technique is LiDAR-based systems in which LiDAR depth sensor, used to create a distance map, can be used in addition to IMU to derivate the position of the mobile station.

In addition, Visible Light Communication (VLC) technologies can also be used as indoor positioning technology carrying information by modulation light in the visible spectrum. Technically it works based on the principle that each light transmitter has its identifier which it compiles into a pulsing light and sends to the mobile station in the reception range. With previous knowledge about the position of each spotlight and the incident angle, the mobile station can estimate their location, as shown in Figure 2.9.

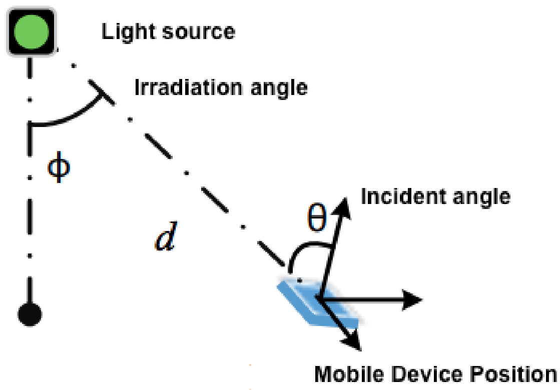


Figure 2.9: Graphical representation of Visible Light Communication technology [14].

2.3.2 Camera-Based systems

Camera-based systems are helpful to extract location and movement information in the same way that human orientation is mainly based on visual information. However, we are not yet able to reach the same accuracy of direction using camera systems [9].

Tipically, there are two possible deployments for a camera-based positioning system whose difference is related to the positioning of the camera. In some cases, the camera is given to the mobile device and location is extracted from the point of view of the mobile device. In other instances, with static cameras, movement information is obtained from the location of a person or object inside the camera stream [9].

For mobile camera systems, some information is typically extracted from the camera pictures including landmarks, feature points, or geometric peculiarities. These are then compared to a database of these features referenced to location. In some systems, specific landmarks with a high probability of re-identification are observed. Some approaches put synthetic landmarks such as barcodes into the environment, while others try to find natural, distinctive landmarks.

Another type of camera-based positioning systems consists in the extraction of the camera ego-motion out of a sequence of images/frames. Therefore, techniques such as optical flow extraction can be used in order to estimate the direction and intensity motion vectors between consecutive frames.

2.3.3 Radio-Based systems

Nowadays, there are several indoor positioning systems based on radio technology. With this type of signals, it is possible to reach extremely high accuracy comparing with outdoor positioning systems like GPS. Another vantage of the positioning systems that operate over radio signals comes from the low cost of radio hardware and radio communication infrastructures are everywhere. GPS reaches the whole surface of the earth, Wireless Fidelity (Wi-Fi) enables location awareness without using GPS, and tower signals of cellular networks provide another infrastructure of radio communication systems.

Figure 2.10, shows the estimated proximity between a mobile device and access points in the area.

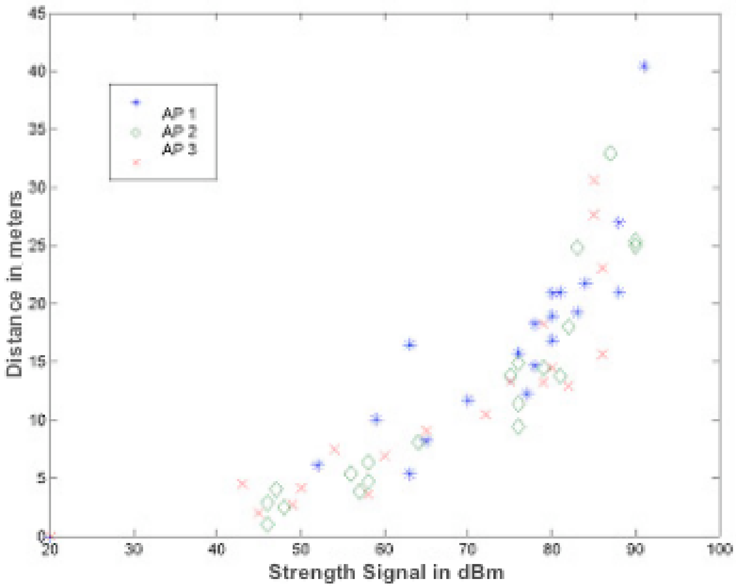


Figure 2.10: Received Strenght Signal of a mobile device in relation to each signal transmitter [15].

In general, positioning systems using radio signals can be based on signal strength information assuming that the signal energy decreases with distance, expressed by the Friis principle (Equation 2.4) while others systems are based on accurate timing information.

Equation 2.4, which relates the power transmitted between two antennas, proves that the power received (Pr) by tag antenna decrease with distance (r) and based on this law, it is possible to conclude that the range of RFID systems is typically insufficient and even more when using passive tags once that this type of tags needs a specific amount of energy, provided by a reader signal, to operate correctly.

$$Pr = (\frac{\gamma}{4\Pi r})^2 \times Gt \times Gr \times Pt \tag{2.4}$$

Inside buildings, however, the length of the propagation path is not always a good indicator for the distance between the sender and the receiver. Thus, these systems are often limited to line-of-sight conditions, and a lot of infrastructures is needed to cover several compartments.

Another type of radio positioning systems is based on angle estimation. In this cases, an array of antennas can be used to determine the angle from which a radio signal has been sent out.

Finally, there is another radio technology capable of positioning devices in indoor spaces that RFID properties. This type of systems is based on two main components. The reader that can be seen as a processing unit that sends radio frequency signals continuously over the air and wait by a response of the tags that can be active, semi-active or passive. Passive tags do not need a current supply. The reader sends energy to an antenna which converts that energy into an RF wave that is sent into the reading zone. Once the tag is read within the reading area, the RFID tag's internal antenna draws in energy from the radio-frequency waves. The energy moves from the tag's antenna to the integrated circuit and powers the chip which generates a signal back to the radio-frequency system. This technology, called backscatter, can also be seen as a variation in the electromagnetic or RF wave, detected by the reader, which interprets the information transmitted by the tag.

Active tags operate similarly but possess their own power supply and thus do not need the circuit that converts the radio-frequency signal to DC signal to power the integrated circuit.

The tags are small and cheap electronic components that can be placed on objects that are intended to follow. When one or more tags receive the reader signal send your identification number as a radio frequency sinusoidal wave modulated in the same frequency, in cases of amplitude modulation (AM) or the same amplitude in cases of frequency modulation (FM).

2.3.4 Inertial systems

Inertial navigation systems based on constant measuring changes in the parameters of the inertial motion unit and therefore, no absolute position can be calculated. Sensors for this type of navigation systems include accelerometer, gyroscopes, odometers, and magnetometers.

Given the inherent inaccuracy of inertial navigation by errors accumulating over time, only a few and very specialized systems for the indoor spaces have been successfully demonstrated. Therefore, the inertial navigation system needs external support, sometimes provided from another positioning system.

Taking into consideration its characteristics, the possibilities of application are reduced compared to other indoor positioning technologies presented. However, the same technology used in this type of positioning systems, called IMU, is used in autopilot system to detect and attenuate the effect of the abrupt variation of directions and acceleration in each axis. This process is explained in detail in Chapter 6.

2.3.5 Audio-Based systems

Audio-based systems use the propagation of audio waves in space in order to locate a mobile device providing ultrasonic signals, to identify locations and provide distance information [9].

Positioning systems that use audio waves to infer relative positions, typically, are composed by a sensor network of ultrasonic microphones that communicating between them can calculate the distance to each of the remaining sensors with which it maintains communication and therefore estimates the relative position of one or more beacons with centimeters accuracies.

Inside buildings, given the characteristics of the materials typically used, the propagation of sound signals is very natural and often better than the propagation of light signal once that a lot of building material reflects and scatters sound waves. This characteristic of audio signals can be seen as an advantage or disadvantage depending on the application case. However, the main characteristic of audio based positioning systems is the slow propagation speed of this type of signals comparatively with the propagation speed of the light signals. This characteristic makes it possible to use several microphones to detect the angle out of which a specific audio signal has been received with high accuracy.

This dissertation explores a solution based on audio signals positioning systems implemented with lateration algorithms developed by Marvelmind Robotics company and presented and discussed in Chapter 5.

CHAPTER 3

Case Study

In the retail industry, there are several solutions to improve control of stock in large warehouses. However, the physical features of these type of buildings are an additional difficulty for the standard stock control mechanisms.

This chapter deal with the company research area where part of the research and development was made as well as the problem which is intended to solve and the different solutions explored during the last months.

3.1 Tyco Retail Solutions

Initially, the thesis proposal was proposed a North American company by Tyco Retail Solutions of Johnson Controls group, a North American company.

The research and development work field of Tyco Retail Solutions focuses on stock control solutions through the development of software and hardware modules which explore the identification technologies like barcode and Ultra High Frequency (UHF) radio-frequency identification. However, at the moment, the main techniques used are based on RFID technologies even if the use of barcode is still integrated into almost all solutions as a complement/alternative to the radio frequency.

Currently, the common developed solutions are based on software management platforms and respective hardware like handhelds, for portable solutions, or big reading gates for motionless cases, applied in reception, storage or dispatch process (Figure 3.1). This type of solutions are designed for to clothing retailers, supermarkets, product manufacturers which enable higher efficiency in the stock control process when it is necessary to distinguish all products or even for products counting procedure in case of product manufacturers treadmills.

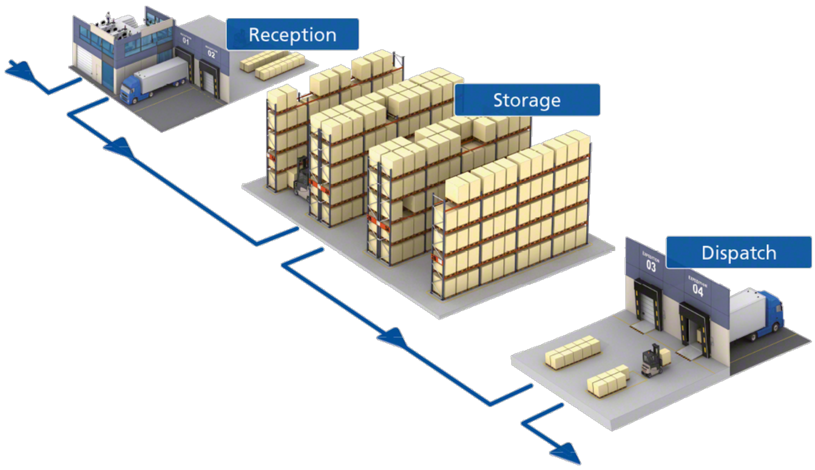


Figure 3.1: Main stages of smart warehouse inventory process [16].

3.2 Problem

However, until the moment there are no efficient solutions for stock control process in large warehouses where typically solutions are not appropriate given their difficult access locations and time needed. In this cases, it is crucial to ensure auxiliary infrastructures and to raise the amount of workforce in order to ensure a full reading in a viable time interval, yet this contributes to the drastic increase in the total cost of the process.

Despite this, in some cases, the existent stock control process is not complete and the process must be repeated frequently once that, in such cases, the most common solutions are not sufficient. The absence of satisfactory alternative solutions for this type of problems that affects all holders of large warehouses is the reason behinds this dissertation proposal.

The RFID technology can be distinguish by the operation frequency range. According to the application scenarios and their characteristics, it can be used Low Frequency (LF) typically operating at 125 Kilohertz (KHz) , High Frequency (HF) operating at 13.56 Megahertz (MHz), UHF that operates in between 860 and 960 MHz depending on the country, the Super High Frequency (SHF) covering frequencies up to 2.45 Gigahertz (GHz) or 5.8 GHz depending of the pattern considerations [17] as shown in Figure 3.2.

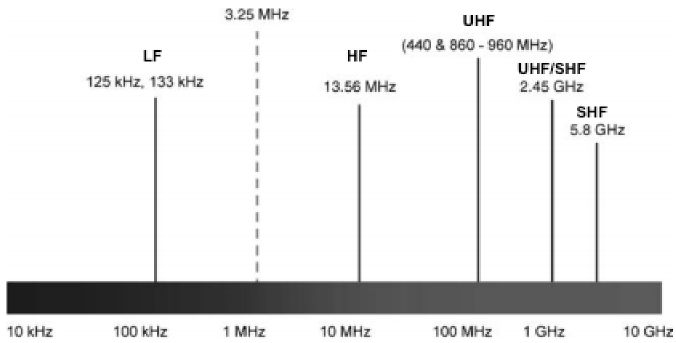


Figure 3.2: RFID radiation spectrum diagram [17].

Commonly there is a distinct set of applications for each type of RFID operation frequency associated mainly to the reading distances required, the communication speeds and also the interference caused by materials.

Typically, LF identification systems provide a short read range around 10 cm and slower read speed when compared to the higher frequencies.

The HF systems with reading ranges between 10 and 100 cm, are usually used for ticketing, payment, and data transfer applications, however, they are more sensible to interference than the systems operating at lower frequencies.

The read range of UHF systems can reach a reading distance up to 12 meters and have a faster data transfer rate than LF or HF.

On the other hand, it is susceptible to interference, but still many UHF product manufacturers have found ways of designing tags/transponders, antennas, and readers/interrogator to keep high performance even in difficult environments [18].

The SHF systems with high data transfer rate and reading range up to 100 meters are used for example, in self-checkout highway systems since these situations require higher communication speeds resulting in short transaction times, of the order of tens of milliseconds, which enables the identification of objects in movement, such as vehicles [17].

The well-known technical problem of UHF and SHF applications is their very modest (or downright poor) ability to pass through most liquids and the human body, which is 80 % water, as well as their generally rather directional propagation. Although this may sometimes be an advantage [17]. Another problem of links operating at these frequencies is the limitation on the remote power supply to the identifier, since the ability to use a small antenna, because of the wavelengths associated with the frequencies concerned, means that energy recovery is rather limited, and therefore it is sometimes necessary to use a local power supply.

Under this problem, there are three main types of transponders (Figure 3.3), also known as tags, which differ in the in the power supply method. The passive tags, basically are remotely powered by the incident radiation, transmitted by the base station, using this energy to power the microchip and produce the response. In case of active tags, for various reasons (the distance may be too long or the base station demodulators may not be sensitive enough), the tag cannot send signals to the base station without having a true transmitter on board. To make this possible, the required response energy is provided by a tag self-battery.

	Active RFID	Passive RFID	Battery-Assisted Passive (BAP)
Tag Power Source	Internal to tag	Energy transfer from the reader via RF	Tag uses internal power source to power on, and energy transferred from the reader via RF to backscatter
Tag Battery	Yes	No	Yes
Availability of Tag Power	Continuous	Only within field of reader	Only within field of reader
Required Signal Strength from Reader to Tag	Very Low	Very high (must power the tag)	Moderate (does not need to power tag, but must power backscatter)
Available Signal Strength from Tag to Reader	High	Very Low	Moderate
Communication Range	Long Range (100m or more)	Short range (up to 10m)	Moderate range (up to 100m)
Sensor Capability	Ability to continuously monitor and record sensor input	Ability to read and transfer sensor values only when tag is powered by reader	Ability to read and transfer sensor values only when tag receives RF signal from reader

Figure 3.3: Most common types of RFID tags [18].

As expected, the difference between both types of tags reflect differences regarding price and dimensions. In warehouses, typically active tags are linked to each product so that it can be distinguished from the others for the sole reason that this type of tags is usually low-cost to the point that in some cases, their reuse is not even practicable. On the other hand, active tags usually are used to identify warehouses sections, shelves, vehicles, machines, etc.

Once that Tyco Retail Solutions is concentrated mainly in the UHF systems given the satisfactory link between the radiation range (up to 12 meters), the communication speed and the cloths containers materials, and that the objective is the identification/detection of each item of clothing in the warehouses, the use of ultra-high frequencies between 865-868 MHz (required range fo Europe [19]) and passive tags, is mandatory.

3.3 Solution

In response to this problem, the United States (US) department of Tyco Retail Solutions launched the challenge of creating a RFID aerial vehicle for this purpose. The idea is developing a system capable of reducing the costs of the stock control process (reducing the workforce and time spent) especially for locations with difficult access. Using UHF identification systems to ensure the reading distances similar to the manual systems like handhelds (4 meters in the best cases), the main objective of the solution is the creation of an autonomous system to perform inventory with minimal human interaction and in the least possible time.

Given the different characteristics of warehouses, the use of a small copter with large load carrying capacity is mandatory once that several auxiliar hardware must be mounted on it like positioning system, RFID reading system, control unit an so on. However, the amount of hardware that should be attached to the copter it's a conditioner of the expected performance, which is discussed further in Chapter 7.

The following diagram (Figure 3.4) shows the components architecture, designed according to the required specifications of the project.

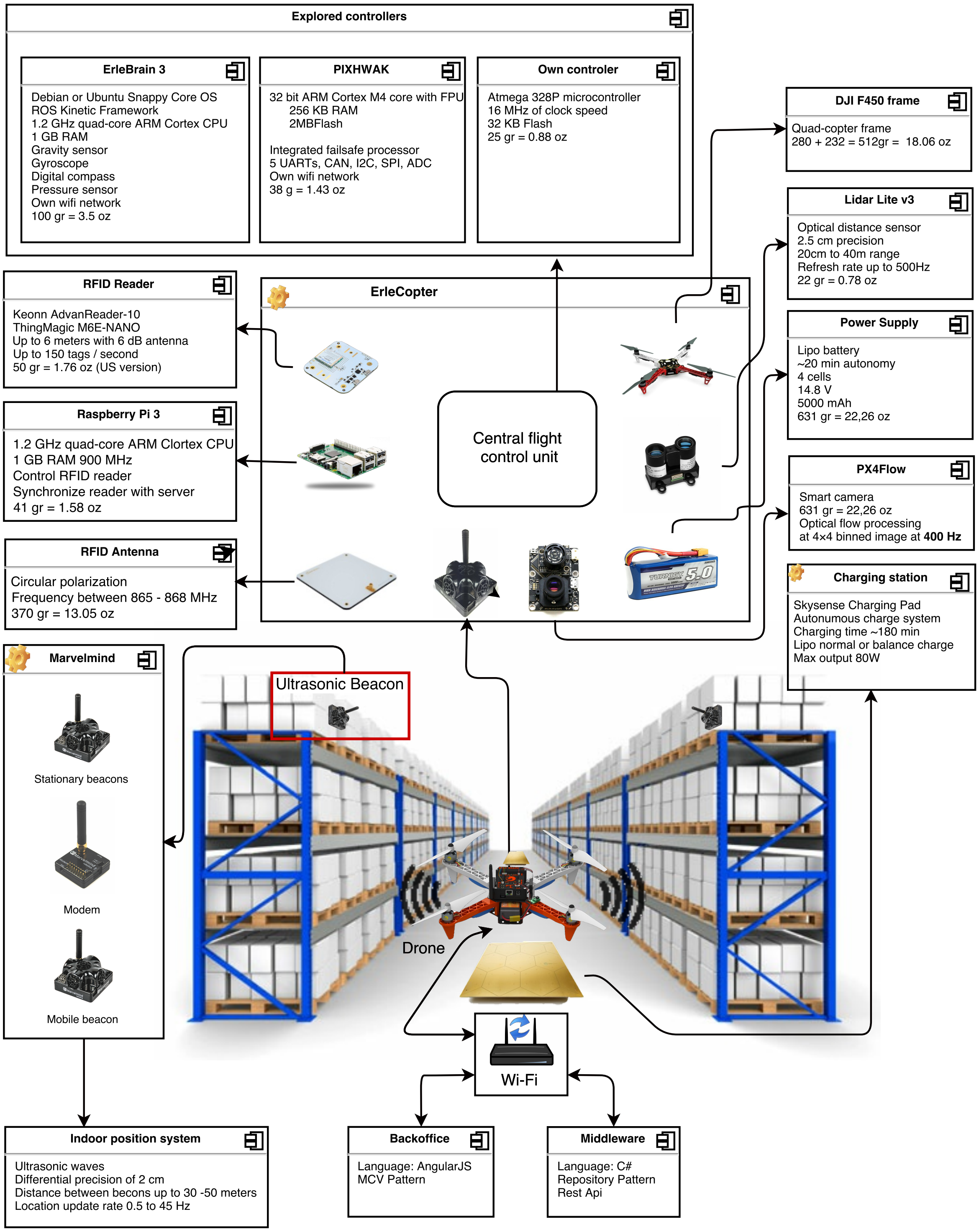


Figure 3.4: Components diagram of the required solution.

As mentioned earlier, the solution designed requires the presence of three main components such as RFID system, IPS and flight controller system. Furthermore, it is necessary the integration with the base station described as Backoffice, which enables the interaction between the users and the system to schedule routes, consult the status of each scheduled flight, view

RFID readings and many other features.

Apart of the user interface developed in parallel for another team, the first issue of the project lies with the necessity of a reliable RFID solution with low power consumption and minimum size and weight in order not to jeopardize flight stability of the quadcopter maintaining the read rates.

Associating these physical limitations and radio frequency specification already mentioned, it was selected a pair of antennas (Advantenna-p11) and reader (AdvanReader-10) without an embedded ceramic antenna, both developed by the Keonn Technologies [20]. Look at the necessity of weight distribution in de drone, not changing its mass center substantially, two antennas have been added to the physical structure even if the reader provides only one antenna SubMiniature version A (SMA) connector and the use of hub to split the signal for many antennas is not supported given its low power interface.

Even so, the RFID system controlled by Raspberry Pi based on Java Keonn frameworks are assembled on quadcopter structure enabling the proof-of-concept of the reading system.

The indoor positioning system discussed in Chapter 5 are selected after a previous unsuccessful attempt of use of a system based on Bluetooth technology and given the price of the entire system and each additional beacon, the system modularity and scalability, covering different areas with a minimal increase of final cost. Composed by a modem or router acting as a base station of the system and a maximum of 99 beacons supported by the interface, that can be placed over the shelves in case of static beacons, allows for scaling across different warehouses areas and layouts, with more or less number of beacons required.

The designed solution also involves the choice of all drone hardware, such as frame, power supply, motors, ESC's, flight controllers and different sensors, even if this decision is risky in comparison with stable and certified working basis such as DJI products or other manufacturers of this type of products that in return are more expensive. However, this choice leads to the necessity of research and integration of all isolated components with central flight control units tested once that in the course of the project several integration problems have arisen.

In the final version of the project, a collision avoidance system should be added as well as the auto charging system using several charging stations placed on specific points on the warehouse plan which act as base stations where each copter can be recharged and fixed in case of anomalies on the system. Although they are features of the final solution, they are not covered in work carried out for this thesis because it is out of scope sub-systems, although, essential to the final product.

During the next chapter, it will be presented the development of the components of the copter, their specifications and integration into the remaining system.

CHAPTER 4

Drone

As previously stated, the UAV's emerged for military purposes, however quickly this technology has been shaped allowing the use for particular and commercial purposes. As known, the objective of this master degree dissertation is based on conventional copters but applied to commercial purposes to improve stock control processes.

The selection of the copter, in this case, could be done in one of two ways: firstly by the construction of a modular drone selecting all isolated components, reducing the costs; secondly by the acquisition of a commercial copter, which allows the development over your central control unit.

After weighing up, it was decided to take a modular approach, buying all required components of hardware individually.

The choice of the main components and construction of the quadcopter was based on the requirement to build something modular, low cost, with the possibility to develop of externals software modules and high load capacity. In this way, several control unit boards are tested in order to find the best solution.

The following section, in the first phase, pretends to present all autopilot boards tested, their characteristics as well as their limitations. In the second phase, the remaining base components of the drone will be explained to perform a short approach to the chosen hardware components and its potential.

4.1 Autopilots

The radio-controlled and autonomous drones, with self-decision mechanisms, are based in a central processing unit used to control all internal system based on their inputs.

In this case, the unit is composed by a Raspberry Pi 3 [21] as the processing core that allows the integration of the auxiliary entities with the specific drone control systems which manage the flight components like sensors, motors, communication protocols, acting over the ESC's.

The Raspberry Pi 3, is a small computer developed by Raspberry Pi foundation of the United Kingdom in 2006 that produce many versions of this in the last years to foment the teaching in Computer Science. The release of this small computer used in this project is the most recent version developed in 2016.

Although this resource has less computational power than the actual computers but the use of this type of computers is required when for some reasons the available space and weight constitutes a limitation.

The last version contains a quad-core Cortex-A53 64-bit processor that operates at 1.2 GHz and 1 Giga Byte (GB) of Random Access Memory (RAM) being necessary to install the version 8.0 of Debian OS.

As core processing unit of the system, this OS running over Raspberry Pi 3 making possible the interaction with all autopilot systems testes through Micro Air Vehicle Link (MAVLink) protocol in case of commercial autopilot shields or by Universal Serial Bus (USB) in case of the homemade autopilot controller developed as the last option.

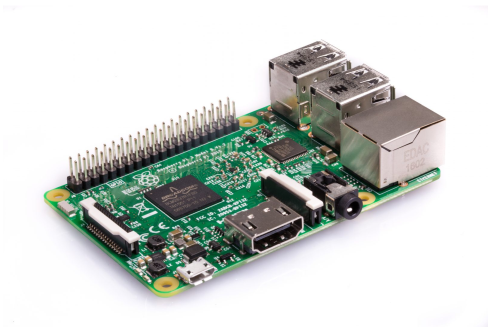


Figure 4.1: Raspberry Pi 3 [22].

As mentioned below, it was necessary a kind of middleware between the core processor unit and the entity responsible for the low-level control of copter.

During the development, several autopilot systems are explored and tested in order to find a more suitable option.

In the beginning, the shield chosen for this task is ROS HAT made by Erle-Robotics [23] presented in Figure 4.2.

This autopilot shield associated with the Robot Operating System (ROS) running over the OS installed on Raspberry PI 3, allows the development of each sub-system entity in C++ and the integration of each of them with the central unit, also described as *Routing node.* The entire architecture of the system is explained in detail in chapter refchapter:movement as well as the communication between each entity belonging to the system.

Figure 4.2: Erle Brain 3 autopilot module [23].

After some research into the other options available on the market, the best solution found for the possible problems of compatibility is PIXHAWK Autopilot [24]. This is an open-hardware project originated from the Computer Vision and Geometry Lab of ETH Zurich (Swiss Federal Institute of Technology) and Autonomous Systems Lab.

Figure 4.3: Pixwhawk autopilot module [24].

Similar to the first option, this shield also supports the integration with Rasberry Pi but using USB interfaces and consequently the interaction with the ROS. This shield also supports the integration with all the external sensors required for the project through Inter-Integrated Circuit (I2C) interfaces but providing only one interface for this type of connection.

In order to provide a future integration of all external components such as Lidar-Lite, PX4Flow, Collision Avoidance System and others, it was necessary to use a I2C expansion board that provides four new ports of this type and in this way, it is possible to connect all systems that use I2C protocol to communicate.

As high-performance autopilots-on-module, this shields can be used as an extension of raspberry pi, helpful to control the dedicated hardware of the drone creating an abstraction layer separating operating system and ROS that runs on it to the input obtained by external sensors and output signal to operate motors.

The communication between Raspberry Pi, ROS Hat and Pixhawk boards is based on MAVLink protocol that is used by unmanned vehicles communications with various autopilot system among them the ardupilot that is used in this project. The communication libraries in

C++ 11 and the diversity of interface ports makes possible the initial integration with all motion stabilizers to improve the flight movement and the obstacle detection sensor required for the last phase of the project.

Even so, after some test, it was concluded that these shields are inappropriate for the task because is not compatible with the horizontal stabilize sensor used (PX4Flow) in the drone and either the autonomous movement or by the radio controller are compromised.

This smart camera sensor based on optical flow processing is one of the best well-known optical sensors, used in drones similar vehicles. Considering the performance of this sensor in the similar applications and their price, PX4Flow emerged as the best option for the project.

With this limitation the choice of a new controller compatible with all external hardware was required, reducing, even more, the little budget available for future development.

Based on this factor and with no more low-cost commercial controllers it was designed a simple homemade controller based on Atmega 328P microcontroller to give us full control over this unit. Starting from an open-source flight auto-level project already developed by Eduardo de Camargo [25], helpful to the initial accelerometer and radio controller calibration process and following flight control.

To compare all controllers acquired the Table 4.1 contains some of the most relevant characteristics of each of them.

Feature	Erle-Brain 3	Pixhawk	Atmega 328P
Dimensions (mm)	95 x 23.8 x 70	81.5 x 15.5 x 50	68.6 x 12.0 x 53.4
Price (€)	199	60	25
Weight (g)	100	38	29
PX4Flow compatibility	No	Yes	Yes
Lider-Lite compatibility	Yes	Yes	Yes
I2C ports	2	1	1
ADC input ports	No	Yes	Yes
Failsafe co-processor	No	Yes	No

Table 4.1: Comparison between Erle-Brain 3, Pixhawk and Atmega 328P controller.

The early calibration stage is fundamental to configure the range values of each channel of the radio control, as well as the IMU resting values.

Given the budget remaining this flight, this controller is the best last choice once that only needs an extra IMU unit and microcontroller.

The development process for this controller will be explained in chapter 6.

4.2 DJI F450 frame

In addition to the flight controllers, all vehicles need a base structure that supports all necessary components to operate correctly. For this type of unmanned vehicles, this structure must obey the set of primary characteristics to enable the correct flight.

Some of this characteristics are based on weight, structure, resistance, flexibility and others. The frame used has about 282g built on ultra-strong materials made by DJI company, which makes the quadcopter very resistant to crashes or other unpleasant events (Figure 4.4).

The arms and plates are designed to protect the ESCs and the battery, and there is enough space between the top and bottom plates to add fragile components. The number of arms used define the number of motors connected by the power distribution board that directly connected to the battery provides the power to all components on the system.

Figure 4.4: DJI F450 frame with motors [26].

4.3 Motors

As it is known, the UAV needs electrical or combustion motors to enable the flight being that this dissertation explores the drones that use electric motors to make the movement possible. Relatively to the electric motors used in the standard drones, these can be differentiated by the operation method, efficiency, durability, noise, rotation and many other characteristics.

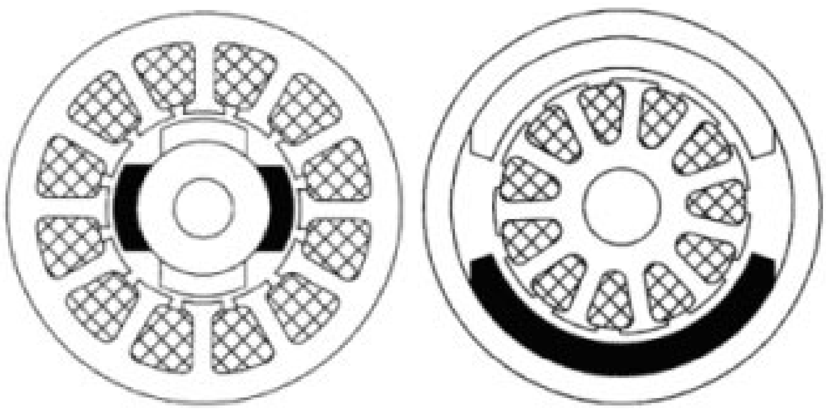
Typically the motors used in this type of application can be the traditional DC or BLDC motors being that the main difference between them is the presence or not of brushes in its structure that improve the performance of BLDC as drone motors.

Besides this differentiation, there are still two types of BLDC motors which are distinguished by the part that performs the rotation (Figure 4.5).There are still two types of BLDC motors which are distinguished by the part that performs the rotation (Figure 4.5).

- **Inner rotor :** Rotation made by inner part;
- **Outer rotor :** Rotation made by outer part;

Feature	Brushed DC Motor	BLDC Motor
Comunication	Mechanical brushesr and commutator	Based on roter position information
Efficiency	Moderate	High
Maintenance	Periodic	None/Low
Speed/Torque	Moderately flat	Flat (No brush friction to reduce useful torque)
Dynamic response	Slow	Fast
Speed	Low	Fast
Electrical noise	High	Low
Lifetime	Short	Long

Table 4.2: Comparison between Brushed and Brushless DC motors [27].



(a) Inner roter. **(b)** Outer roter.

Figure 4.5: Different types of BLDC motors [28].

In this project are used outer roter BLDC three-phase motors with two coils per phase with 950 Motor velocity constant (Kv), this constant is an index that establishes the relation between Rotations per minute (RPM) and supply voltage in Volt (V). With this constant, the maximum number of rotations per minute is obtained multiplying velocity constant by supply voltage according to the Equation 4.1.

$$RPM_{max} = Kv \cdot V_{supply} \tag{4.1}$$

Take into consideration that the power supply provides regulated outputs between 14.8 and 16.8 V, the rotations per minute of the motors is between 14060 and 15960 in ideal conditions. The reason for choosing this specific motors is related to their load bearing capacity taking into account the additional components required for the system and the maximum extra weight that drone can support with each type of motors.

4.4 Electronic speed controllers

ESC is mechanisms that control motor parameters like rotation direction and speed. This integrated circuit typically receives a Pulse With Modulation (PWM) signal from flight control unit and power from the power distribution board or directly from the power supply operating directly over the motor. These mechanisms also provide current sense information of each motor phase which contributes to the constant readjustment of the power supplied to the motor.

One of the main limitations of these circuits is related to the maximum current supported (30 Ampere (A) in this case) and consequently to the maximum power output.

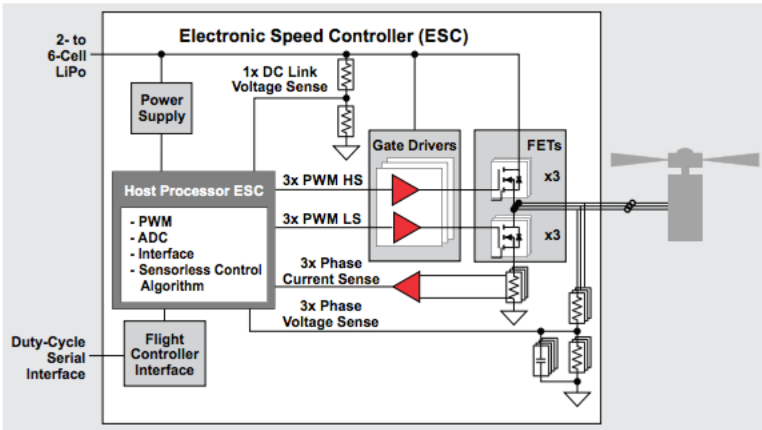


Figure 4.6: BLDC motros electronic speed controller [29].

4.5 Lider-Lite v3

Lidar-Lite (Figure 4.7) is a distance optical sensor developed by Garmin [6] for the unmanned vehicle like drones or robots, used as a vertical stabilizer to correct the vertical movement of the drone. This is possible because, with vertical movement deviation without any order of the radio controller or from the autonomous algorithm, the autopilot mechanism detects all unexpected movements and force the correction to the correct value without any user interaction.

This sensor operates in the range between 5 centimeters and 40 meters with (±2.5 cm) of precision in distances upper than 1 meter communicating the distance value calculations by I2C protocol to the PIXHAWK Autopilot controller.

The use of this type of sensor that operates autonomously, without any user control, can be a limitation of the project because the change of environment around the drone can influence the correctness of the movement. In practical terms, this sensor can compromise vertical movement of the drone when some object or person is detected below the drone and in this case, the drone will correct their upright position because the distance between the drone and the object is different of the distance between the drone and the ground. This limitation can be attenuated through the autonomous flight algorithm in constant interaction with indoor positioning system but not fully corrected.

Figure 4.7: Lidar-Lite v3 rangefinder sensor [30].

4.6 PX4FLOW Smart Camera

PX4FLOW (Figure 4.8) is an optical flow sensor based on a machine vision CMOS image sensor for indoor and outdoor applications with very high light sensitivity. Optical flow is estimated on an ARM Cortex M4 microcontroller in real-time at 250 frames per second at a subsampled resolution of 64x64 pixels using a CMOS machine vision sensor once that CMOS sensor-microcontroller system is low-power, low-latency and low-cost and therefore suitable for micro aerial vehicle applications [31]. The system contains an ultrasonic range sensor that is used to measure the distance towards the scene and to scale optical flow values to metric velocity values.

In a practical approach, this sensor system provides in real time a velocity and direction estimation which makes possible its operation as a horizontal stabilizer during the flight detecting flow variations that are used to calculate the irregular movements in the horizontal plane. Therefore it provides a fundamental movement control when there is no movements infection caused by the wind or human touch during the flight.

This optical sensor is in constant communication, using I2C protocol, with PIXHAWK Autopilot system that oper according to the information coming from multiple sensors like PX4FLOW and Lider-Lite that in association perform a total movement stabilizer for every motion axis of the drone.

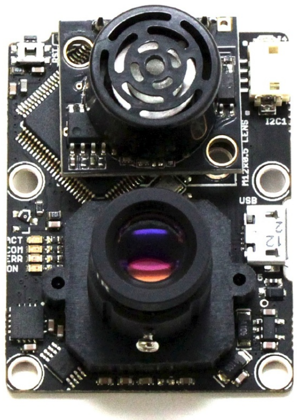


Figure 4.8: PX4Flow smart camera [32].

4.7 Power supply

Knowing that most of the components in the system are electronic components they need sufficient energy to operate. In this case, given that the power supply must be portable, is use a Lithium Polymer (LiPo) Battery with 5A of capacity and four cells, each with 3.7V.

To supply power to specific components that operate at 5V, a voltage regulator is included to the system, resulting in the increase of energy dissipation in the form of heat, reducing the continuous operating time of the system.

Although it is a high capacity battery, with all extra hardware the flying time is approximately 10 minutes depending on the flight mode used.

CHAPTER 5

Indoor position

As mentioned earlier, the positioning techniques can be applied in two main areas: Outdoor and Indoor.

Indoor Positioning can be seen as a mechanism or technique to obtain the position and in some cases, also the orientation, of a mobile object or person within an enclosed space such as warehouses.

Marvelmind indoor positioning system is composed of one or more mobile and stationary ultrasonic beacons that operate by radio interface in a free band and the modem where all beacons are connected through wireless. Based on trilateration process (Figure 5.2), for another words, the mobile beacon position is calculated based on the propagation delay of ultrasonic waves to a set of stationary beacons but this method only works with, at least, 3 stationary beacons.

However, Marvelmind Robotics company recommends the use of a higher number of stationary beacons than the minimum, to enable an active redundancy of the system.

With this architecture, we can know the mobile beacon position with high precision (± 2 cm) providing this information to the control unit. For each application scenario, it is possible to make some changes in mobile and stationary beacons settings like enable or disable ultrasonic sensors (RX1 to RX5) contained in each beacon (Figure 5.1), change number of periods, change operation frequency and many other parameters in order to improve the location.

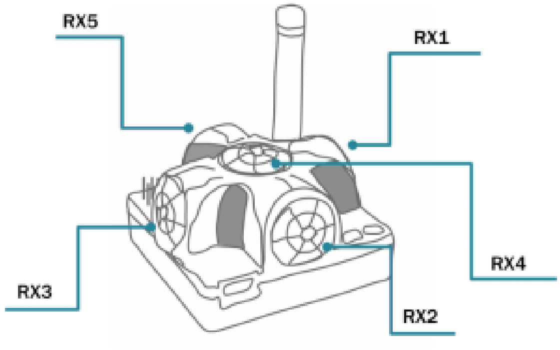


Figure 5.1: Distribution of ultrasonic sensor in each Marvelmind beacon [33].

The settings applied to each beacon depends on the operation mode, most of it is the same for beacons that operate as stationary or mobile.

The system makes it possible to specify some of the configuration parameters for each beacon allowing the adjustment of the system behavior according to the application scenario. Some of the application scenario characteristics, such as environmental noise, warehouse layout or even construction materials can influence the communication between the stationary and mobile beacons.

In order to find the ideal configuration for this application scenario, Marvelmind engineers were contacted and after some discussions about the surrounding application environment, drone characteristics, and beacons layout in the whole area, significant improvements in transmission signals were observed.

The results obtained with the variation of same configuration settings are present and discuss in the next section as well as the main settings values used in each case.

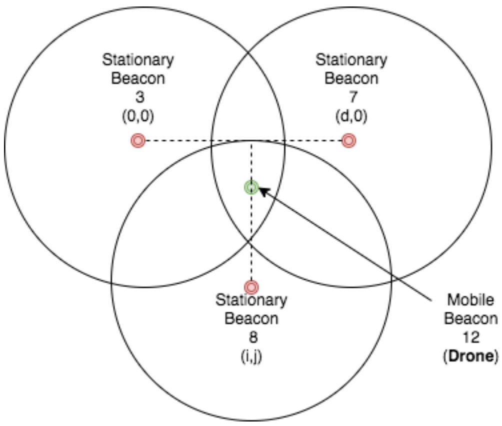


Figure 5.2: Graphical representation of trilateration method.

5.1 Mobile becons

The indoor position system must contain at least one mobile beacon, however, in drone set used for this dissertation, two mobile beacons are required because autonomous flight algorithm needs some geographic or relative orientation and once that in the beginning this algorithm use geographic orientation based on compass module integrated in control unit board but this is not possible because some electromagnetic interferences manipulate the compass data and in some cases, warehouse construction materials, influence the sensor values. With this problem, it was necessary to find a solution that makes possible to obtain stable orientation values from stationary beacons.

This alternative requires the use of two mobile beacons in the drone set separate by 30 centimeter (cm) to each other and receiving the ROS message of both sensor, the routing node can distinguish the emitter sensor of a specific message. This approach relies on a Time Division Multiple Access (TDMA), so, if two mobile beacons are active at the same time, they share the same system bandwidth and the data received coming from both beacons alternately but it is possible to distinguish by the beacon address sent in every message.

This makes it possible the calculation of the exact position of the center of the drone starting from the position of each mobile beacon and the direction calculated in IPS node. In the official version (v4.5) of Marvelmind firmware, this process is not possible because it supports only one mobile beacon and therefore only provides the information related to this beacon. The firmware release used that allows pairing of two mobile beacons is a non official version provided by the company as a test version with the objective to report existing bugs in order to help the company to detect and correct bugs concerning the acquisition of position values of mobile beacons and calculation of relative orientation values.

Seen as master communication module, the mobile beacon responsible for communicating the precise position and orientation of the drone with Raspberry Pi provide data messages with the following parameters:

- **Hedge id :** Mobile beacon identification;
- **Timestamp :** Temporal mark;
- **Cartesian coordinate x :** Mobile beacon x position;
- **Cartesian coordinate y :** Mobile beacon y position;
- **Cartesian coordinate z :** Mobile beacon z position;
- **Degree :** Using two mobile beacon this topic is the degree between yy axis and drone orentation.

All process requires that only one mobile beacon is connected to Raspberry Pi using USB port and this beacon acts as master of the communication system sending the information of all mobile beacons.

After the processing and filtering all information received in control unit, output control signals that operate over the ESC are calculated based on a routing algorithm. These signals are nothing more than the flight variables like yaw, pitch, roll and throttle explained in Chapter 6.

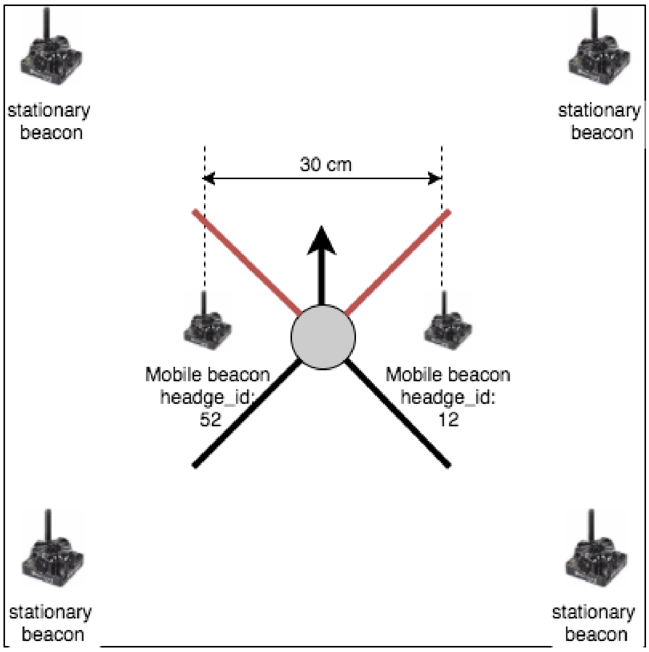


Figure 5.3: Graphical representation of the distribution of Marvelmind beacons in a simple application scenario.

As previously stated, the mobile beacons needs a specific configuration to operate correctly. The values presented in Table 5.1 results of Marvelmind engineers discuss in order to maximize the performance of the system and reduce the occurrence of failures that can compromise the indoor positioning system.

Parameter	Value
Device address	12
Mode of work	TX + RX
Number of periods	5
Filter selection	19 KHz
RX1	enable
RX2	enable
RX3	enable
RX4	enable
RX5	enable
Pair mode	pair
Address of paired headge	52
Location against center	right
Base of pair in centimeters(1 to 255)	30

Table 5.1: Most important settings of mobile beacon 12.

Most of the parameters are coincident with default values proposed by Marvelmind. However, after many tests, parameters like number of periods, that means the number of messages with mobile beacons information sent to Raspberry Pi every second, is changed from 50 to 5 because for values higher than 5 the number of inconsistent values received in central unit increase and is no more appropriate to the autonomous flight algorithm because successive invalid position values can compromise the flight of the drone.

5.2 Stationary becons

The stationary beacons are used to make possible the trilateration method of the mobile beacons. They have specific configurations differents of mobile beacons presented on Table 5.2 and rules to be placed in the test area.

With regard to the distribution of beacons into the area, they must be placed horizontally on the walls. However, for navigation of copters, the company recommends that some beacons are placed on the ground to maximize ultrasonic signal convergence.

The position of each stationary beacon is based on distance to others beacons of the same type. Because this characteristic, the distance between the fixed beacons is the main limitation of the system as referred in Limitations section.

Parameter	Value
Device address	8
Mode of work	TX + RX
Number of periods	5
Filter selection	19 KHz
RX1	disable
RX2	disable
RX3	disable
RX4	enable
RX5	disable

Table 5.2: Most significant configuration setting for stationary beacon 8.

Unlike mobile sensors, not all ultrasonic sensors contained in each beacon are active. This occurs because, with stationary sensors placed on the walls, with the vertical orientation, only the ultrasonic sensor directed towards the interior of the tests area needs to be active. Some tests are made using different active ultrasonic sensors and it was concluded that there is no improvement of system performance when more sensors are used.

This conclusion is also in line with the Marvelmind recommendations about the influence of the number of active ultrasonic sensors for situations with abnormal surroundings conditions.

5.3 Router or modem

As the central control of the system, the router (Figure 5.4) acts as a system monitor. It can be placed anywhere within ratio convergence (up to 100 meters radius) operating over a priority ratio protocol used for communication and synchronization.

Figure 5.4: Marvelmind router or modem [33]

5.4 Dashboard

The dashboard is the Marvelmind manage interface that allows the configuration of all available parameters of the system. The main characteristics of the dashboard interface are presented below.

- Visualize beacons position and state;
- Configure beacon settings;
- Consult table of distances between all beacon on the system;
- Freeze/Unfreeze the map;
- Monitor ultrasonic signal from one beacon to another one;
- Create sub-maps or delimitated areas;
- Monitor the levels of energy of each beacon;
- Update firmware for beacon and router.

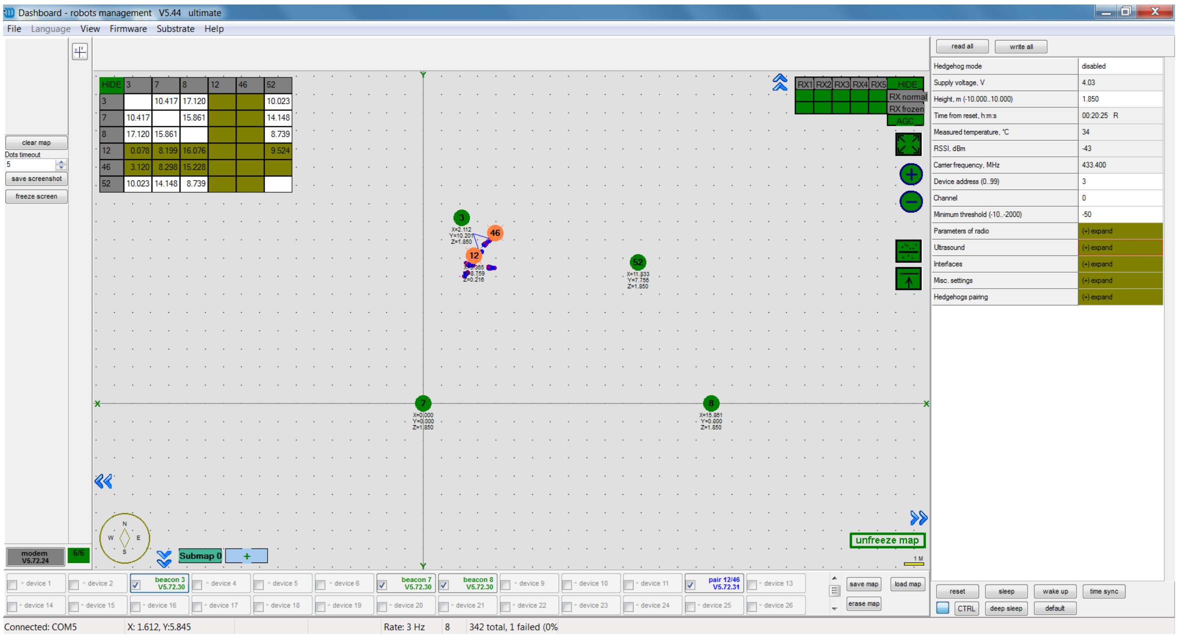


Figure 5.5: Dashboard interface.

This interface is fundamental to monitor the behavioral changes of the system variating the distribution of the beacons in the area, the communication setting of each beacons and the resulting signal received for each mobile and stationary beacon. According to the operation mode of the beacons, they can operate as transmitters or/and receiver, so, the state of each beacon depends on the signal received from the beacons with which he communicates. In this way, for correct operation mode, each beacon must be supported for the signals transmitted from at least three stationary beacons in 3 dimensions (3D) scenarios. For a correct operation of the system, the table of distances presented in dashboard must be "white" and with all values available. This shows the distances between all beacons integrated on the system, providing information about the communication status between every pair of beacons integrated on the system. An example of tables of distances in and respective beacons layout in correct and incorrect operation are shown in Figure 5.6 and Figure 5.7 respectively. In these images, also the three different operations states of the mobile beacons are represented with different colors of the circles that represent each beacon.

Since that the signal noise increase with the rotation of the motors, is expected that the worst performance of the system occurs during the flight with some aggressive movements or in the exact moment of the takeoff, as represented in Figure 5.7. In this case, at least one of the mobile beacons is represented by transparent circles and the positioning and orientation values are inconsistent and can compromise the flight.

In cases that both mobile beacons are in the orange state, the system can operate even with some communication failures and positioning and orientation values may contain a significant error associated with. The worst operation state occurs when a circle represents at least one of mobile beacons with transparent color and with this, the position and orientation values is no longer trustable and the flight must be aborted. In resume, the Table 5.3 represents all possible operations states of mobile beacons.

State	Description	Operation
Blue	Beacon in correct opertaion	Correct
Orange	Communication signals have some errors but can opere	Some errors in position and orientation values
Transparent	Received signals are insufficent to allow the calculation of the position and orientation	System are compromised The flight must be aborted

Table 5.3: Description of mobile beacons operation states.

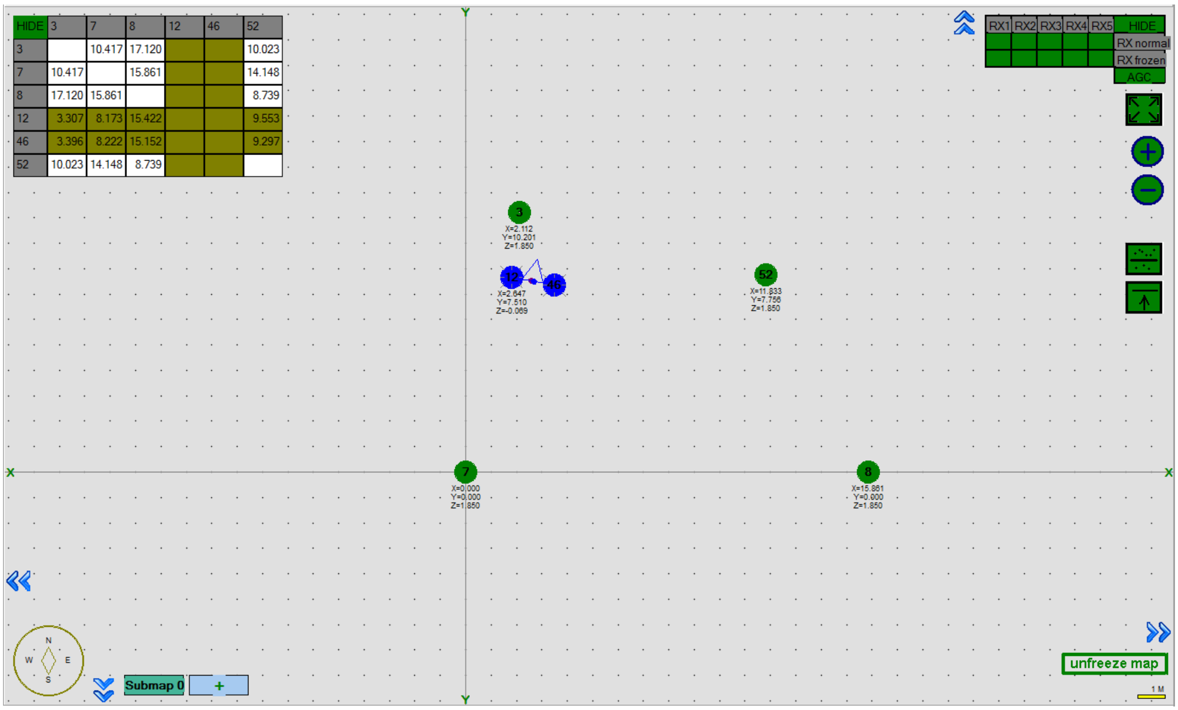


Figure 5.6: Table of distances, beacons distribution map and operation state of each beacon with routers off.

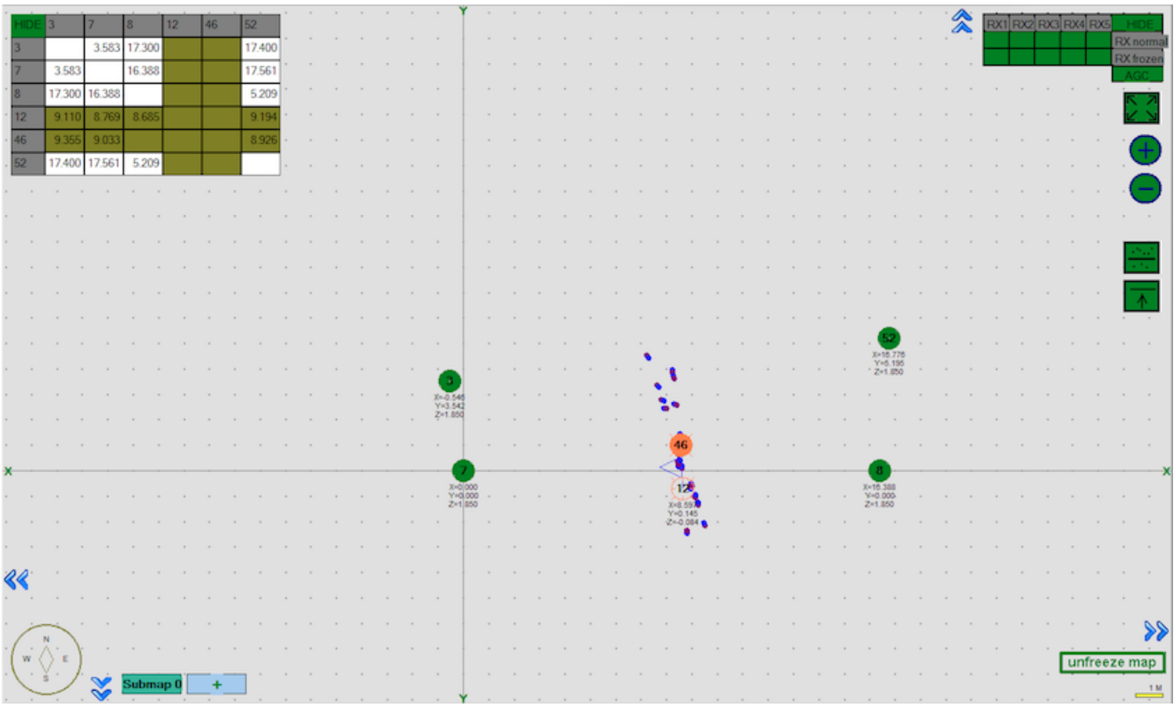


Figure 5.7: Table of distances, beacons distribution map and operation state of each beacon with routers on.

5.5 Limitations

Given that the system works with ultrasonic signals it is known that this type of signals are influenced by multiple factors like temperature, pressure, humidity, environmental noise, distance and others. Within the scope of this dissertation, some of this factors should be considered in order to avoid system failures or incorrect positioning results.

Marvelmind robotics develop some mechanisms to prevent the consequences of some of the refered factors, but in extreme cases, these are insufficient to ensure the correct operation of the system.

The temperature, for example, influences the propagation of the ultrasonic signals on about 0.6 m/(s* °C), due to temperature variations the error associated to the localization can be changed. However, this problem can be corrected because Marvelmind system allows to setup temperature of air on dashboard settings. Unlike this, in this project, the most significant limitation of this type of sensor is about the environment noise. Even that Marvelmind develop additional features to filtering the external noise, and allows the manual configuration of the frequencies affected by the implemented filters, 19 KHz by default. In our case, the noise created by the drone routers is too strong and if the distance between drone and stationary beacons is to small the system functionality can be affected.

This problem makes the system unable to work correctly using a minimum number of stationary beacons in small spaces because the drone proximity to any stationary beacon compromises the communication between this beacon and the others. Since the conditions for the trilateration process are not met, the indoor positioning system fails and the drone loses location information.

Given the maximum distance between each pair of beacons is up 30 meters in normal conditions or up to 50 meters in laboratory conditions and the systems support a maximum of 99 beacon connections, the problem related to the signal noise can be resolved using N+1, N+2, ... , N + 94 stationary beacons, with N equals the minimum number of stationary beacons to enable the trilateration process. For another words, increasing the number of stationary beacons and the distance between them, some redundancy levels are created increasing the system robustness. However, if the drone gets closer to one of the stationary beacons, this beacons will fail but once that the minimum number of stationary beacons remains assured the system operates correctly. To comprove this hypothesis, some test is made in a warehouse with similar characteristics to a real target scenario and the results are presented in Chapter 7.

5.6 Conclusion

In conclusion, the active indoor positioning system, based in ultrasonic signals, used in this dissertation have high precision and after system tests and discussions with manufacturer company, an ideal configuration to practical scenarios has been achieved. This is possible because functional experiments in the warehouse are made, although it is not possible revel the company name due to data protection and privacy issues. This performance tests, made in real target scenario allowed the differentiation between theoretical and practical configurations, therefore for different target scenarios different configurations and setups should be created and tested once that there are infinite warehouse layouts with characteristics and materials that can influence the performance of the system. The pratical results of the configuration and beacons distribution into application scenarious are presented in Chaper 7 and also in Appendices [1, 2, 3, 4] of this document.

The system limitations described above shall be taken into account and the solutions proposed to attenuate these limitations must be respected to obtain a sufficient system operation. Concerning to the number of stationary beacons used in the system, it depends on the objective and the covered area, but if possible it is recommended to maximize the redundancy levels increasing the number of stationary beacons to values higher than the minimum number with which the system works. Regarding the number of mobile beacons, the difference is related to the necessity of orientation values once that to objectives that need orientation values without using any external sensors, the use of two mobile beacons are mandatory otherwise one is sufficient.

CHAPTER 6

Autonomous control algorithm

As previously mentioned the entire developed control system operates over a flexible framework whose operation is allowed by the OS installed on Raspberry Pi. In this case, the recommended version of ROS (Kinetic Kame), released on May 23rd of 2016, was installed and configured over a modular version of Debian OS provided by Erle Robotics.

From the installation and configuration process results in a system architecture composed by a typical Linux kernel and Docker core to provide automation in Linux application deployment inside software containers and modular layers containing ROS and ROS 2.0 providing hardware abstraction, networking and update modules. The docker core acting as the intermediary between our containers and Linux Kernel, providing isolation of each container from the rest part of the OS, safeguarding the system if something is wrong with any container update [34].

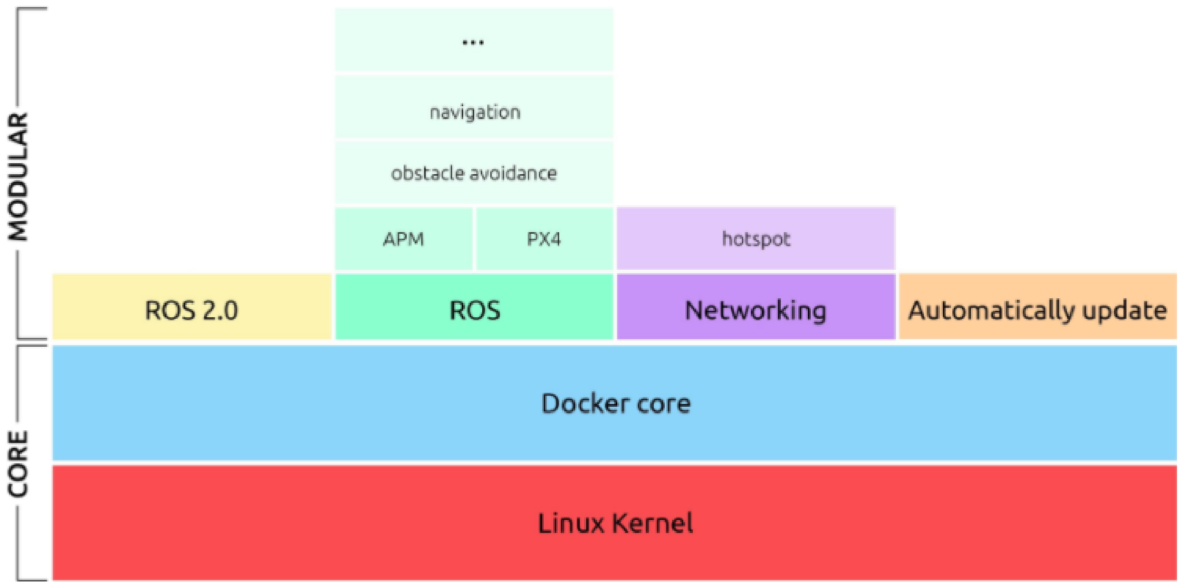


Figure 6.1: Modula Debian OS architecture [34].

6.1 Sytem architecture

The main reasons for the use of ROS ecosystem are related to the exhaustive list of features available with this framework. Features like the modularity and the automatic messages parsing between each node, the publish/subscribe system to share information between nodes asynchronously for some required tasks and for another way, the services when synchronous request/response interactions between processes are mandatory. So, these features make possible the interconnection between different nodes by their message types defined earlier as a .msg extension to publishers/subscriber or .srv for services.

Exploring the capacity of modular development of ROS 2.0 the entire system are separated into different nodes, developed in C++, for each system entity that interacts by services as enable/disables trigger for each available publisher belongs to another node. The node architecture and the interaction of each of them are shown below in Figure 6.2.

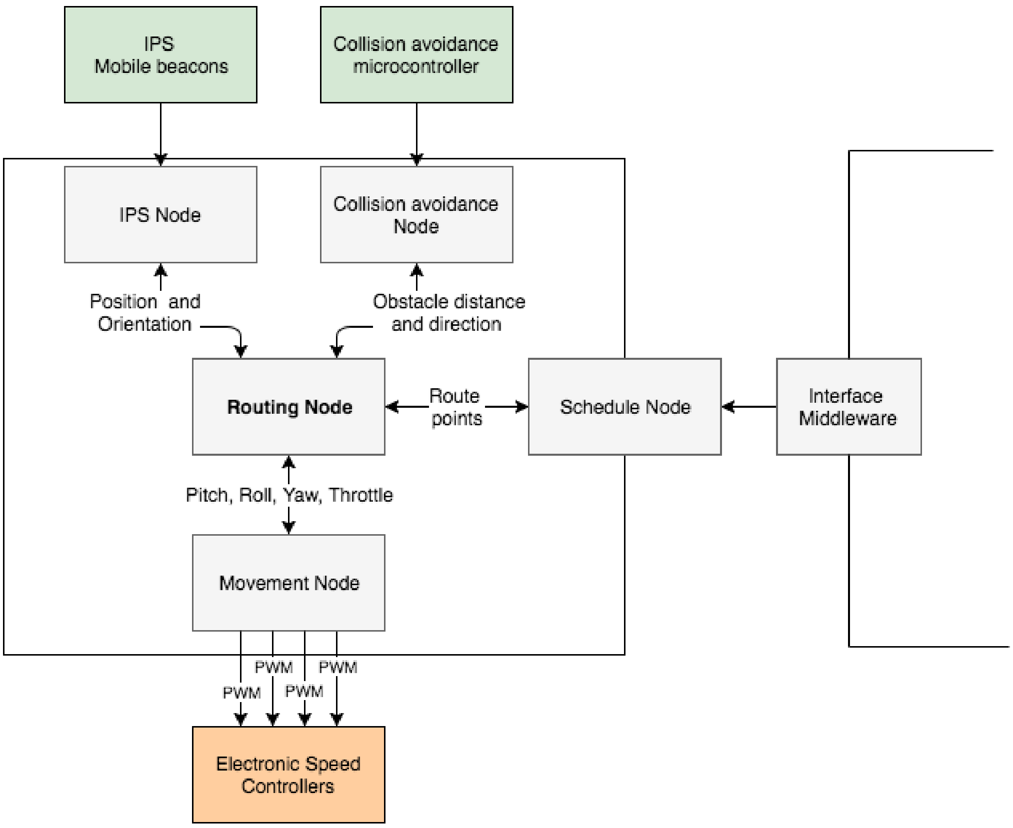


Figure 6.2: Node architecture of the developed system.

All processes are controlled by Routing node that acts as a central control unit according to the input provided by each secondary entity. The flight order is triggered by the reception of a route from the schedule node defined by date, hour and a set of points and created by the user in the interface. With the reception acknowledgment message sent in opposite direction, some route validations are made following specific rules such as:

- The first point must be coincident with the original position of drone but with different height.

- The last point must be coincident with the position of an existing base but with different height.
- All points of the trajectory must belong to the free flight zone.
- The sum of minimum distances between each pair of points must be less than the predefined value.

Exploring the ROS features relative to the services and publishers/subscribers, with the exception the schedule node, all nodes in the system contain at least one service acting as the trigger of their publisher or subscriber. The Figure 6.3 shows all services and publishers or subscribers associated to each node and also the structure of each message exchanged between the entities.

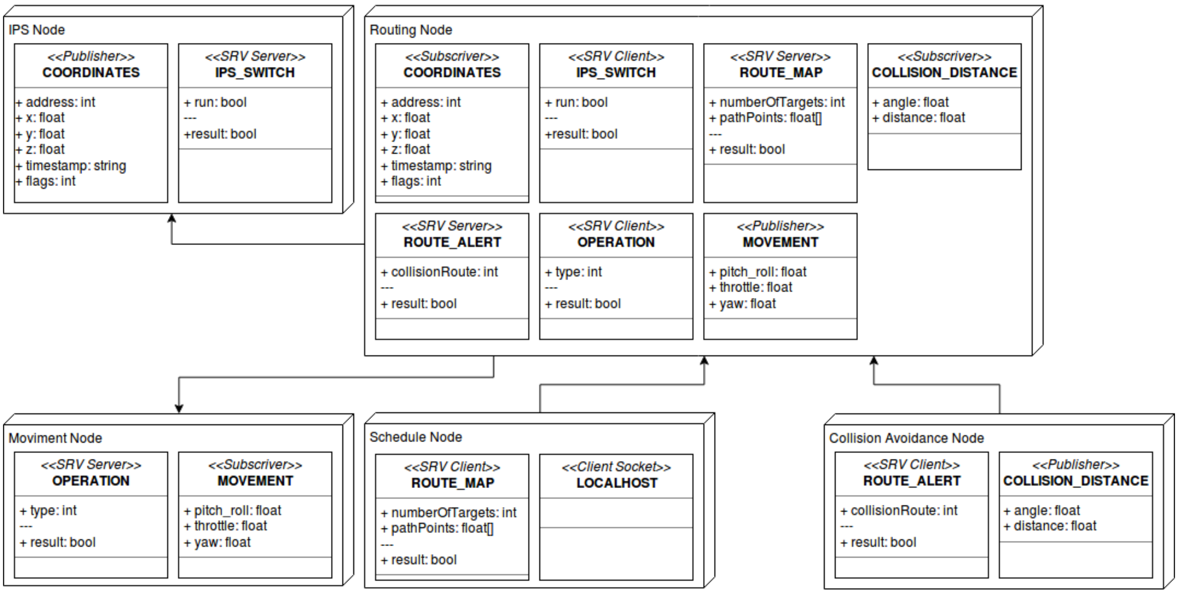


Figure 6.3: Communication entities (Publishers, subscribers and services) of each node of the system.

The process begins the reception of the route in routing node from schedule unit using *ROUTE MAP* service which allows the communication with all secondary nodes belonging to the system according to a specific order.

IPS publisher nominated *COORDINATES* that provides to routing node position coordinates and orientations values is the first secondary node to be agreed by *IPS SWITCH* service of the routing node. After that, If everything is correct with IPS this share consecutively with routing node the position and orientation data.

After validation of the correct operation of the IPS module, the activation proceeds to the activation of collision avoidance *COLLISION DISTANCE* publisher that ideally share the information about the presence of obstacles, their angle around the copter and respective distances in centimeters. One more time, with correct operation validation of this module the central node proceeds to the activation of movement node.

Once all nodes are active, the route node begins the movement values calculation like pitch, roll, throttle and yaw sending this values to movement node as *MOVEMENT* publisher messages.

6.2 Routing algorithm

The central architecture node called *Routing node* is the entity responsible for producing flight control values that when sent to *Movement node* are converted to input motors signals and filtering to prevent possible sudden variations of direction and acceleration.

These flight values (yaw, pitch, roll and throttle) are the result of a complex operation based on indoor positioning coordinates (x, y and z), the orientation of the copter also provided by IPS from each pair of consecutive route points and, in a future release, by the collision avoidance algorithm in order to recalculate an alternative route around the obstacle.

Movement calculation process repeats indefinitely for each route point that needs validation. The validation of each point in the route has a maximum error of 20 cm in each coordinate axis. For another words, a route point can be validated when the drone position is up to 20 cm range volume of the route point coordinates. The choice of this value is related to the time for recognition of the points, with the less error the time for validation to each point increase and for too small error values the points can never be recognized and the flight come in an infinite loop because the drone cannot validate this target position.

To simplify the algorithm responsible for this operation, in this version of the project, the roll values are defined as a constant value of 1500, that represents null motion value. Pitch is set to 1550 in case of moving forward or 1500 for no movement in the horizontal point, once that the operating range for each flight variables are between 1000 and 2000 in perfect calibration conditions.

The throttle control signal is the most simply motion value once that represents the motion in the applicate axis. So, in this case, the value is calculated based on the difference between two horizontal planes defined by the current position and the target position. However, to prevent some abrupt accelerations that can compromise the safety of the flight, the maximum warehouse height is taken into consideration in order to attenuate the output value according to the proximity to the limits defined by the ground and the maximum reading horizontal plane.

On another hand, the yaw value that traduces the required rotation of the copter to perform the movement between two points of the same horizontal plane defined by two cartesian coordinates (x,y) are influenced by the current position of the drone, its orientation angle relative to the y-axis and the angle of the line segment defined by this current two dimension coordinates and also target coordinates, also in relation to the y-axis.

The necessity of ensuring a specific processing order led to the creation of a kind of mealy final state machine (Figure 6.4), in which the transactions between states are triggered by the node services and respective response until movement start, by the validation of each target point contained in the route map and by the detection of obstacles.

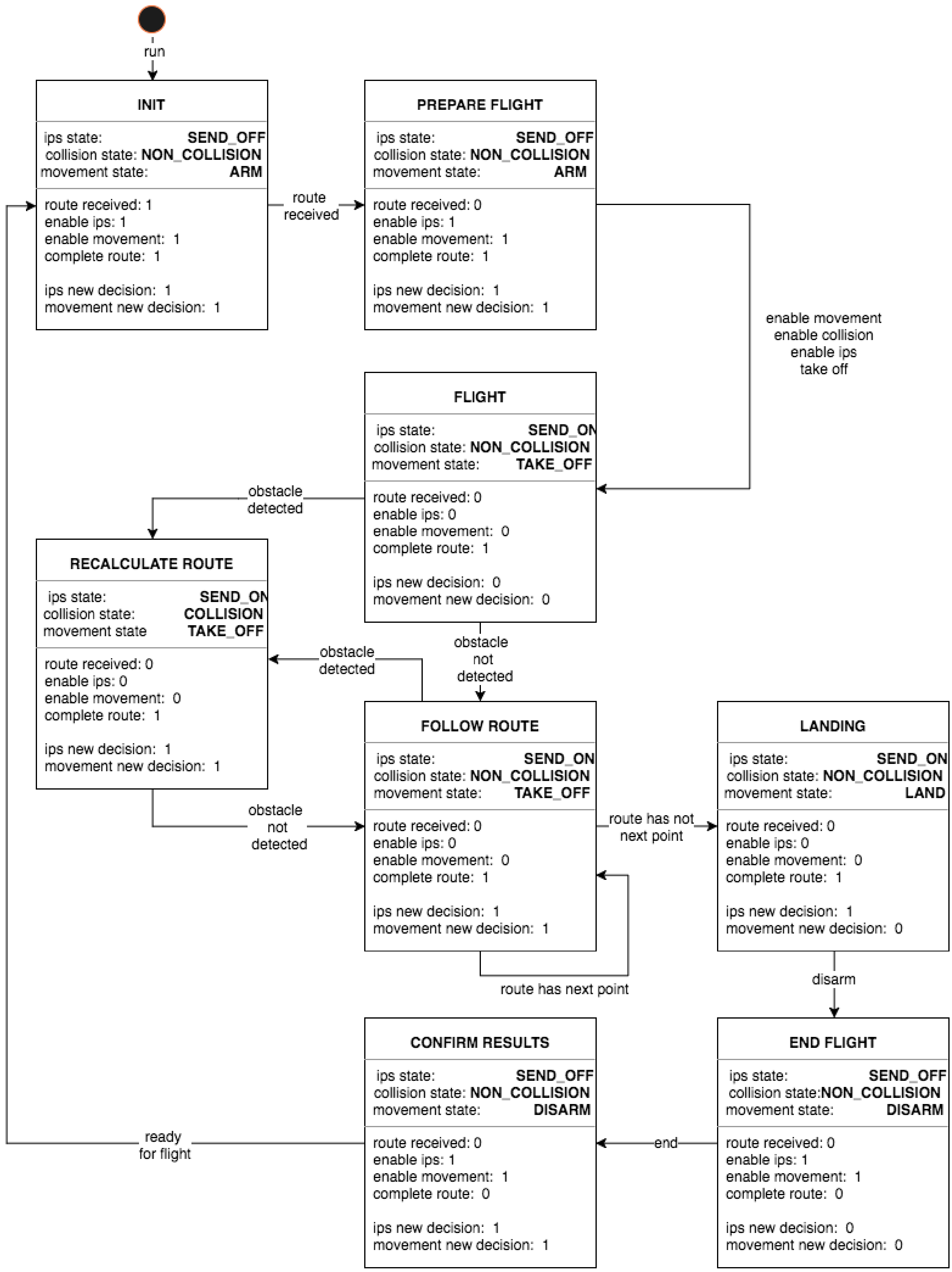


Figure 6.4: Mealy final state machine of control system.

The *FLIGHT* state reflects the correct operation of all nodes of the system and the ability to start the flight, designated by *TAKE OFF* operation. The following two states are relative to route point validation and route recalculation process in order to avoid obstacles. The validation of the last point of the route triggers the transition for *LANDING* consisting of reducing the throttle value to perform the landing. In this state, the route was completely disabling all node publishers and send to interface middleware the RFID readings. The Figure 6.5 shows a simple scenario used to test this algorithm.

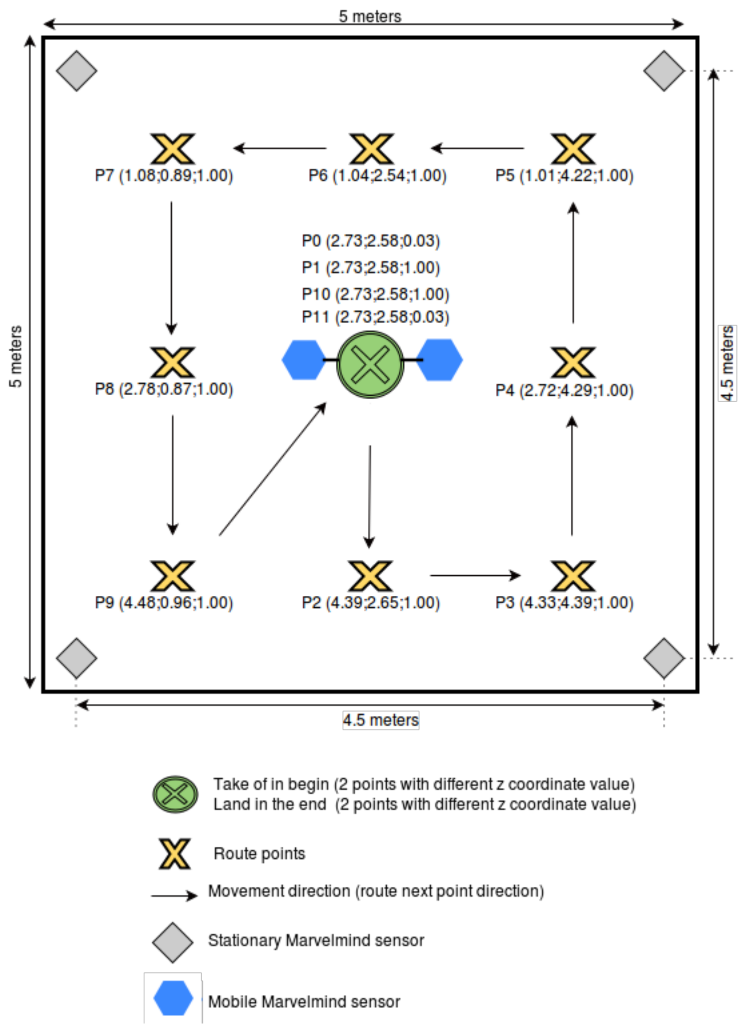


Figure 6.5: Example of an autonomous flight route.

6.3 Atmega 328P controller

The last flight controller tested, as mentioned before, is based on the open hardware and software auto-leveling project. In this case, the core unit is an atmega328P microcontroller and an IMU-6050. This inertial motion unit contains three-axis accelerometer and gyroscope in a single chip and it is accurate enough, as it includes 16-bits analog to digital conversion hardware for each channel. Using I2C-bus as an interface with the microcontroller, it is possible to obtain the values related to acceleration and gyroscope for each rotation axis.

The initial project already provides calibration and test tools and algorithms and a simple flight algorithm which operates with radio-controller input values. Starting from this principle, several PID controllers have been added to the original flight algorithm to correct motion values of each degree of freedom (yaw, pitch, roll and throttle). During the flight test, the capacity of debugging is required and using serial communication the interaction between the microcontroller and raspberry pi it was possible. However given the clock speed of the microcontroller used (16 MHz), the sending process in each cycle causes some processing delay, about 10 ns, and this delay was unsuitable for the flight stabilization. As a solution for this problem, the update of the values in raspberry pi was made at regular time intervals causing the loss of some data.

After this process, the next step was the integration of a height sensor to enable the vertical stabilization of the copter. Using lidar-lite v3 referred in Chapter 4 and I2C-bus as interface with microcontroller was created a PID controller for this sensor data, calculating an error value e(t) as the difference between the desired setpoint (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms. In this case, it acts as an accurate and responsive correction to a control function of the throttle.

For each type of copter and the corresponding type of motors distribution on the frame, there are specific equations for each motor associated with its position in the structure. Being the drone used for the performed tests a typical quadcopter with a well known motors distribution, as shown in the Figure 6.6, the control values for each motor can be calculated from the equations [6.1, 6.2, 6.3, 6.4] , based on each existent PID controller output that can be powered by each rotation axis input from the radio-controller or autonomous flight algorithm.

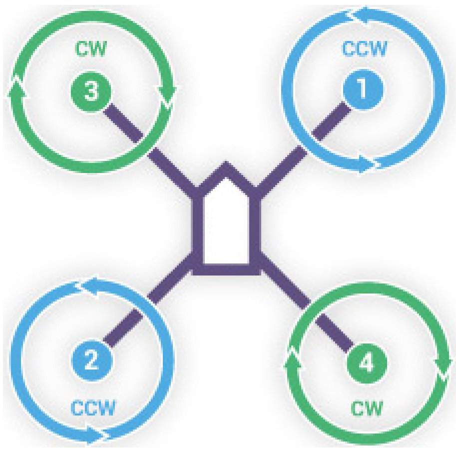


Figure 6.6: Direction of rotation of the quadcopter motors [35].

$$ESC_1 = throttle + pid(rangefinder) - pid(pitch) + pid(roll) - pid(yaw) \qquad (6.1)$$

$$ESC_2 = throttle + pid(rangefinder) + pid(pitch) + pid(roll) + pid(yaw) \qquad (6.2)$$

$$ESC_3 = throttle + pid(rangefinder) + pid(pitch) - pid(roll) - pid(yaw) \quad (6.3)$$

$$ESC_4 = throttle + pid(rangefinder) - pid(pitch) - pid(roll) + pid(yaw) \quad (6.4)$$

A similar process could be developed to integrate the PX4Flow as an optical flow sensor also referred in Chapter 4. This sensor composed by a camera and a pre-processing unit provides the direction and intensity vectors of the horizontal motion based on adjacent frames captured by the camera. Also using I2C-bus as the interface with microcontroller it could be possible the horizontal stabilization of the drone using two additional PID's, one for each motion axis, associated with each ESC equation previously presented.

After some tests and revisions of the terms (Kp, Ki, Kd) belonging to each PID it was concluded that with the decrease of battery power, the behavior of the system changes because for each motor control value resulting from the expressions presented above, the power available for the respective ESC reduces with decreasing battery power. In response to this problem, it was conceived an electronic circuit called resistive divider and expressed by the Equation (6.5), capable of quantizing the battery charge based on the analog signal obtained from the power supply and sharing this information with microcontroller makes possible the correction of the values applied to each ESC.

This circuit translates the relation between the maximum, current and the minimum voltage of the power supply in an interval compatible with the capacity of the microcontroller that in this case is between 0 to 5 V to analog input ports.

$$Vout = \frac{Vin \times R2}{R1 + R2} \quad (6.5)$$

Given the characteristics of the battery selected, formed by four lithium polymer cells with a nominal voltage of 3.7 V, the power supply voltage varies between 13.2 and 16.8 V. Being R1 a resistor of 2360 ohm and R2 a resistor of 100 ohms the resistive divider circuit produces an output range between 4.17 and 5.00 V. Although it is a small variation range, the system can use this information as a power offset for the ESC's.

As we already know, independently of the controller used, before any flight, a calibration and sensors test process is required. In case of commercial controllers like Erle-Brain 3 and Pixhawk, there are many high-performance autopilot systems to perform this type of tasks and even for the flight such as APM Planner.

The main problem with this tools is that typically they are generalized for various purposes and vehicles which makes it difficult to use them in specific situations as the purpose of the ideal product resulting from this dissertation. In this case, several problems have been arisen with the attempting to use this type of autopilot in indoor locations and with the integration of external sensors like Lider-Lite and PX4Flow, since that the total control over the autopilot system it's not possible starting from an unknown development base.

On the other hand, in case of Atmega328p controller, this process was made with total control of the user and with full access to the source code. Being a simplified flight system, its possible to control and test all modules manually with no abstraction layer between the software and hardware that in this particular case hinders the development.

6.4 Conclusion

In this phase of the project, the system architecture is already developed based on ROS using C++ to make possible the integration of each different part such as schedule, positioning, collision and routing modules. Beginning with the schedule and positioning entities, no problems have been raised and they operate as expected. Unlike this, it's not possible to develop a solution capable of stabilizing the drone as a test base of the autonomous flight algorithm. The development associated with the last controller tested, base on Atmega328 microcontroller, was interrupted after the full damage of Lidar-Lite sensor during the flight tests.

After the conclusion of the internship period at Tyco Retail Solutions and with a potential need for the acquisition of material, it was decided to complete the development phase of this thesis.

Aware of this problem, many alternatives for these limitations are exposed in Chapter 8 in case of an increase in the budget available for the project once that all core system developed can be applied to other copters that opera based on ROS, only with a few configuration changes. This feature enables the acquisition of a new control system or even an entire drone being this the best option taking into account the current state of the project and the difficulties found related to the different acquired controllers.

CHAPTER 7

Results

In this chapter, it will be presented the results of each practical phase explored during this thesis as well as the final structure of the drone with all components and modules coupled.

In the first section, it will be presented the final setup with all physical components such as indoor positioning beacons, RFID system modules, and other.

In the middle section, it will be presented the results of the RFID system and the influence of when linked to the drone.

In the third section, it will be presented the results of the indoor positioning system taking into account the interference produced by the drone routers.

At last, it will be presented the possible results of the autonomous flight algorithm and controllers tested.

7.1 Quad-copter setup

One of the main reasons for the difficulties of flight felt is related to the modification of the structure changing the original mass center of the copter, components addition and consequently the weight of these modules. The final setup is shown in Figure 7.1, has approximately 2268 gr of weight which represents an increase of 2 times the original weight. This fact associated to the recommendation of the frame manufacturer relative to the transport of not more than 1500 g causes many difficulties in the control of the quadcopter flight and a decrease of autonomy to about six minutes.

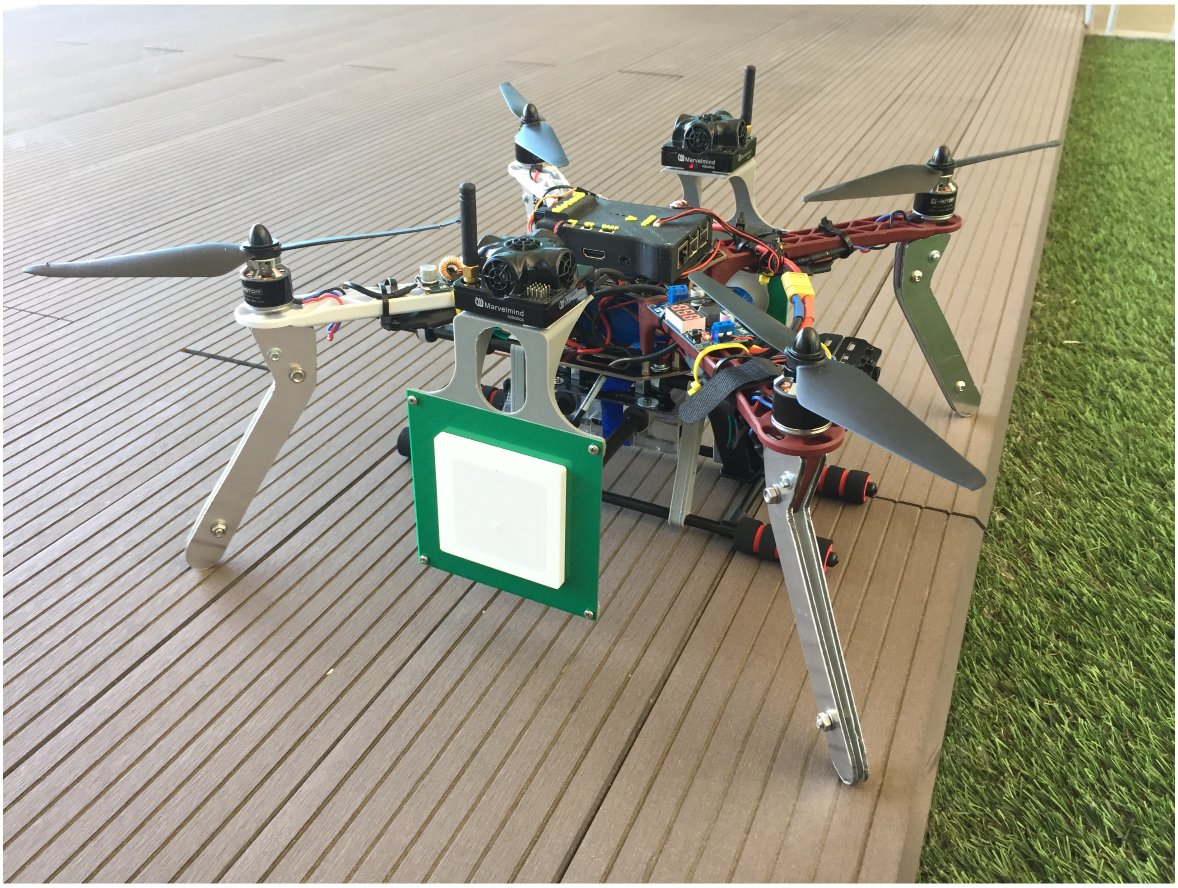


Figure 7.1: Quad-copter final setup.

Beyond weight, as previously mentioned the mass center has been changed with the assembly of all required components, mainly with the assembly of the RFID antennas, Marvelmind beacons and their supports designed especially for these antennas and with Marvelmind support extension.

These supports were distanced of 30 cm for two main reasons. In the first, the RFID system only provides satisfactory results for distances greater than 15 cm between each antenna and the center of the copter. The second reason is related to the recommended distance between Marvelmind mobile beacons to ensure reliable orientation values referred in Chapter 5.

7.2 RFID system

In the first phase, several tests were made to the RFID modules such as antennas and reader as isolated modules to create ideal reading patterns. This perfect reading rates, exploring the maximum capacity of the entire readings setup, enable the comparison between the reading rates obtained with the system linked to de drone in different positions in stationary state or even during the flight.

The performed tests are based on the ability to perform successful readings in practical scenarios represented by a set of 16 tags coupled to clothing items distributed in boxes with no predefined order.

The results of each situation tested are presented in the following charts according to the physical setup shown in Figure 7.2.

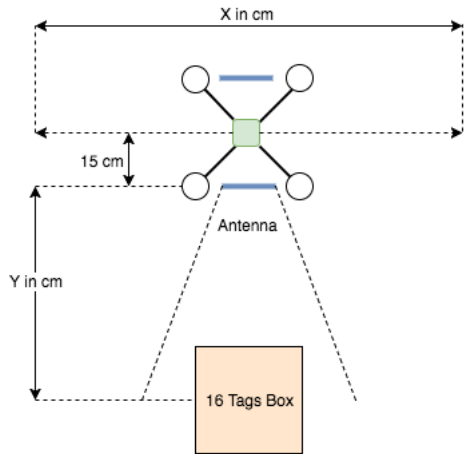


Figure 7.2: Illustration of the setup for flight and no flight tests.

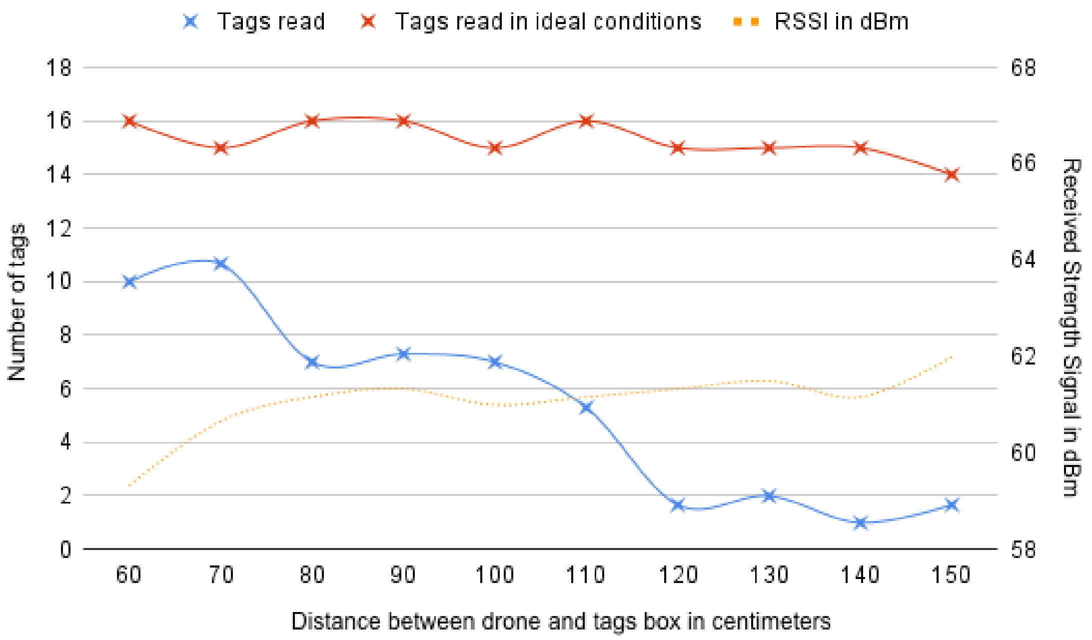


Figure 7.3: Comparison between tags reading results with RFID system isolated and coupled to the drone, moving it 200 cm in X-axis.

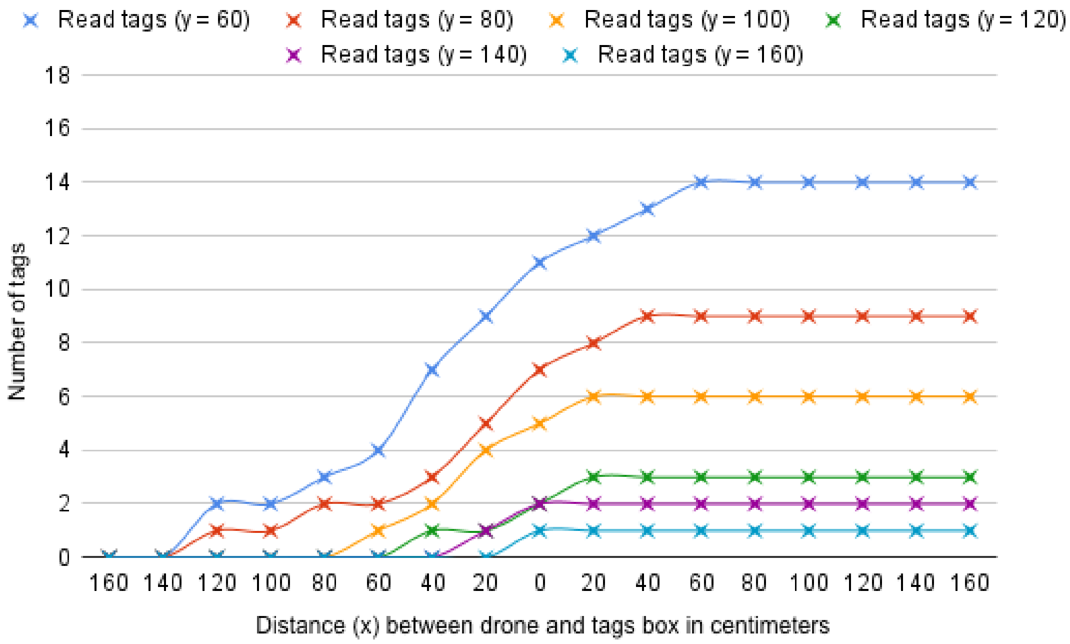


Figure 7.4: RFID performance during the flight approximation to the tags box and for different perpendicular distances.

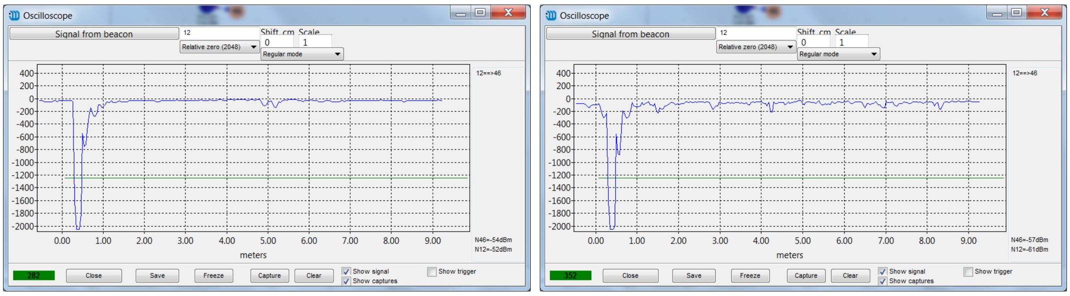
The results presented in Figure 7.4 are an approximation to the reality because the flights are performed using the radio-controller without any stabilization system which makes difficult the control of the distance between de drone and the tags box. This is the central reason for the minimum value of proximity is 60 centimeters.

7.3 Indoor positioning system

These type of localization systems, based on ultrasonic signals, has proved more appropriate and efficient enough for this type of applications.

Although some problems related to the noise produced by the routers have arisen during the flight, because of the small number of beacons used, as mentioned in Chapter 5, they have been reduced or fully resolved.

Figure 7.5 shows the comparison between the signal received by a mobile beacon (beacon number 12 in this case) from a stationary beacon belonging to the system in small spaces with routers off and on respectively.

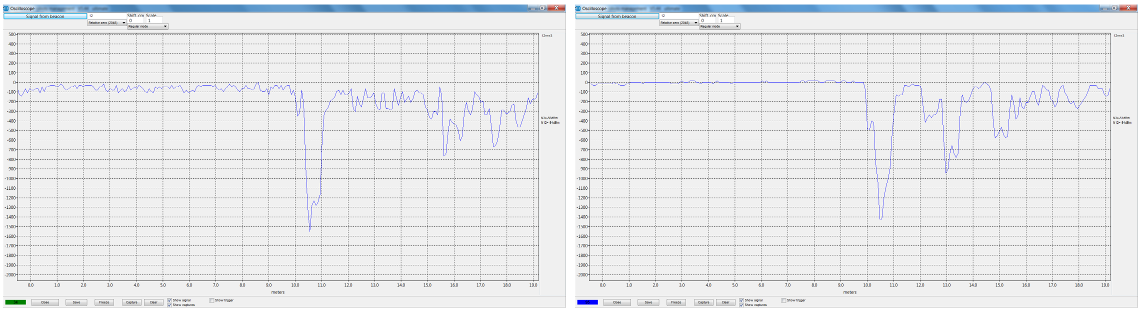


(a) Received signal by beacon 12 with drone routers off. **(b)** Received signal by beacon 12 with drone routers on.

Figure 7.5: Ultrasonic signal received by beacon 12 with enbale and dissable drone routers

After the conversation with the manufacturer, this interference does not present any more a problem. The results of the tests performed in the real warehouse, even with the minimum number of stationary beacons, was deemed satisfactory in the noise interference resistance, in the precision of position and ability of maintenance of the correct system operation.

Figure 7.6 shows the graphics of the signal coming from one of the stationary beacons to one of the mobile beacons assembled in the drone for the tests performed in the real warehouse before and after the new configuration applied.



(a) Without specific configuration applied **(b)** With new configuration applied

Figure 7.6: Ultrasonic signal received by beacon 12 from static beacon 3 spaced 10.5 meters

Yet, the use of more than the minimum number of stationary beacons is recommended to prevent system failures triggered by the approach of the drone to some stationary beacon.

To measure the minimum distance between drone and stationary beacons to guarantee that the indoor position system does not fail, many distances was been tested. Beginning at 1.0 meters and successively increased until the system resisted to the noise. When the distance of approximately 4.0 meters, the system remains in a correct operation even with maximum noise levels. These tests are made with 3 stationary beacons, the minimum number of beacons, but as was said earlier, with more stationary beacons the minimum distance can be reduced because in real scenarios the drone will not be at a minimum distance from several stationary beacons and if at least 3 are in the correct operation the system does not fail.

Relatively to the distance between stationary beacons, the system behavior shows that over distances of 22 meters (approximately, depending on the test spaces) the localization and orientation performance is affected significantly.

The following graphs show the failure rate variation of the localization and orientation information with the distance using a square sensor arrangement.

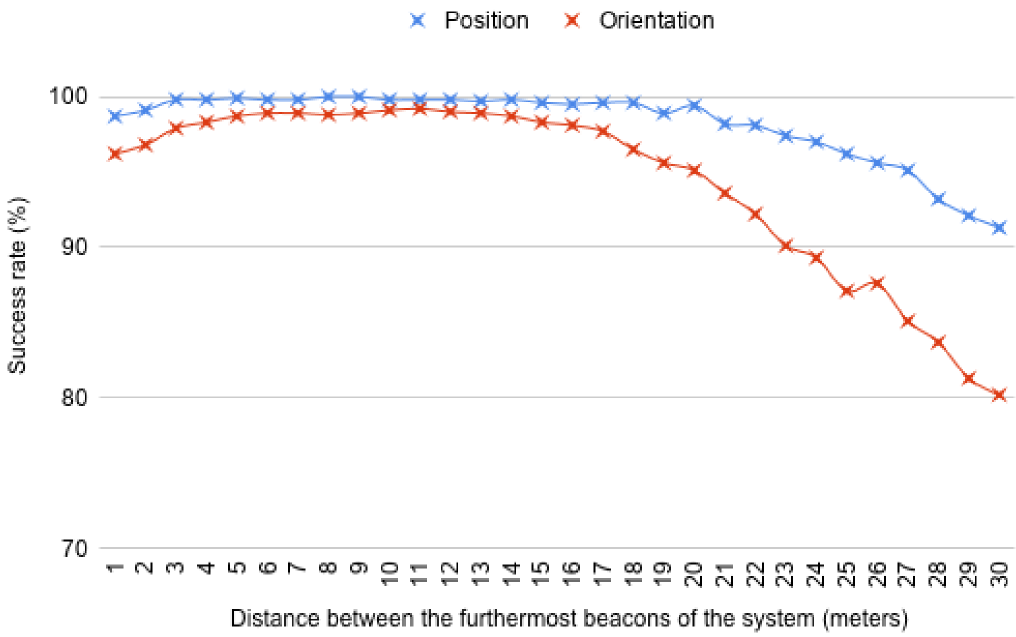


Figure 7.7: The indoor positioning system success rate with increasing distance between stationary beacons.

CHAPTER 8

Conclusions

During the research, development and testing phases of this thesis was possible to conclude that the use of drones in order to improve the performance of the inventory processes in warehouses it is possible and affordable.

One hand, the lower weight, lower power consumption and low-cost RFID system built for this proof of concept allow verification of the reasonable identification range and consequent acceptable read rates. On the other hand, the indoor positioning system explored, provides reliable and precise results of position and orientation of the drone to the control algorithm.

With these conditions, it has been possible to develop a central control unit, capable of managing all the entities of the system, further allowing the future integration of other modules designed, such as the collision avoidance unit.

In contrast, the modular drone built and the components used, proved to be a wrong choice for the objectives of this dissertation given the integration difficulties of the parts and global power consumption.

8.1 Future work

As previously mentioned, the main problem of the developed system consists in the integration of the flight controller hardware modules. However, there are some solutions on the market to resolve this issue. DJI drone manufacturer, develop a commercial drone of Matrice series [36] which allows the ROS integration and development and even an external collision avoidance system that operates based on a set of cameras. With a larger budget, it can be possible the resolution of the practical difficulties, if the project justifies the additional investment of more than 3 599 euros only for the drone and even more for collision avoidance system.

In case of the radio frequency identification system, to detect and identify the products in on the warehouse shelves, different reader and antennas should be explored to improve read rates and maximize the distance from the shelves and achieve levels of performance within the required standards by the retail industry.

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Appendices

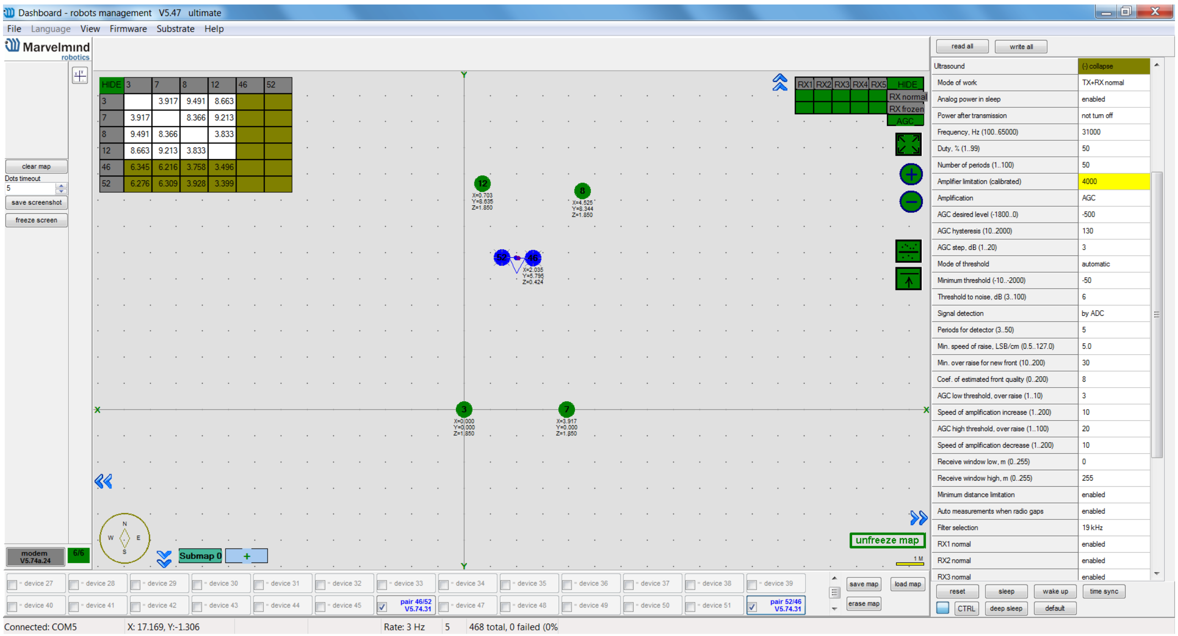

Figure 1: Dashboard configuration settings and layout with all ultrasonic sensors active in each stationary beacon.

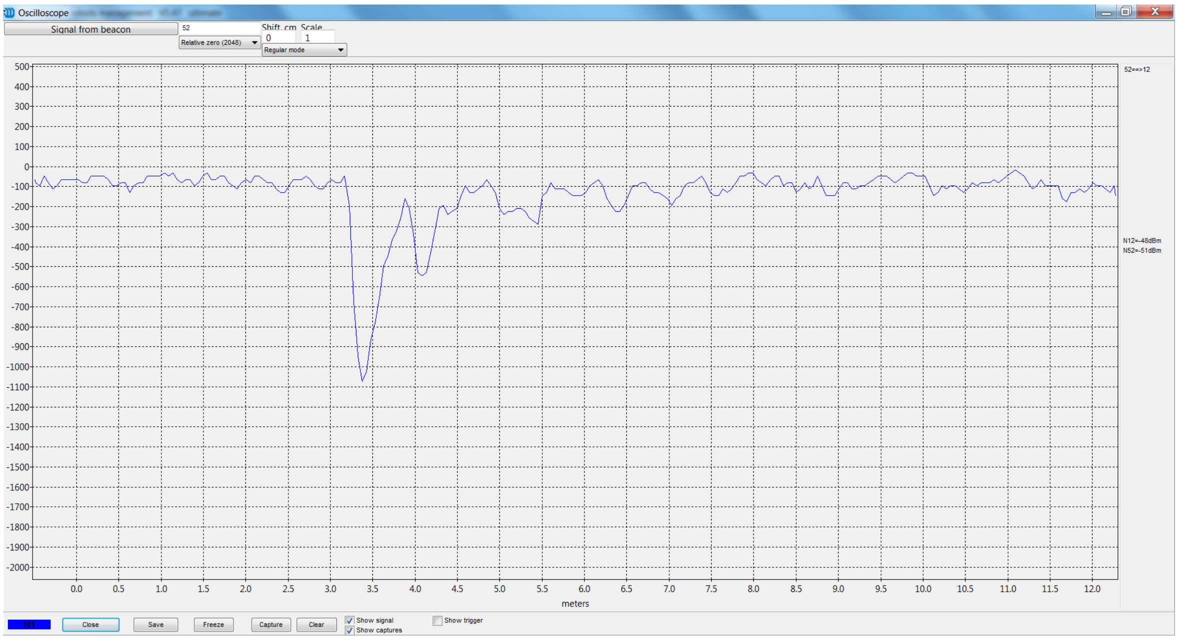

Figure 2: Received signal by mobile beacon 52 from stationary beacon 12 with all ultrasonic sensors active in each stationary beacon.

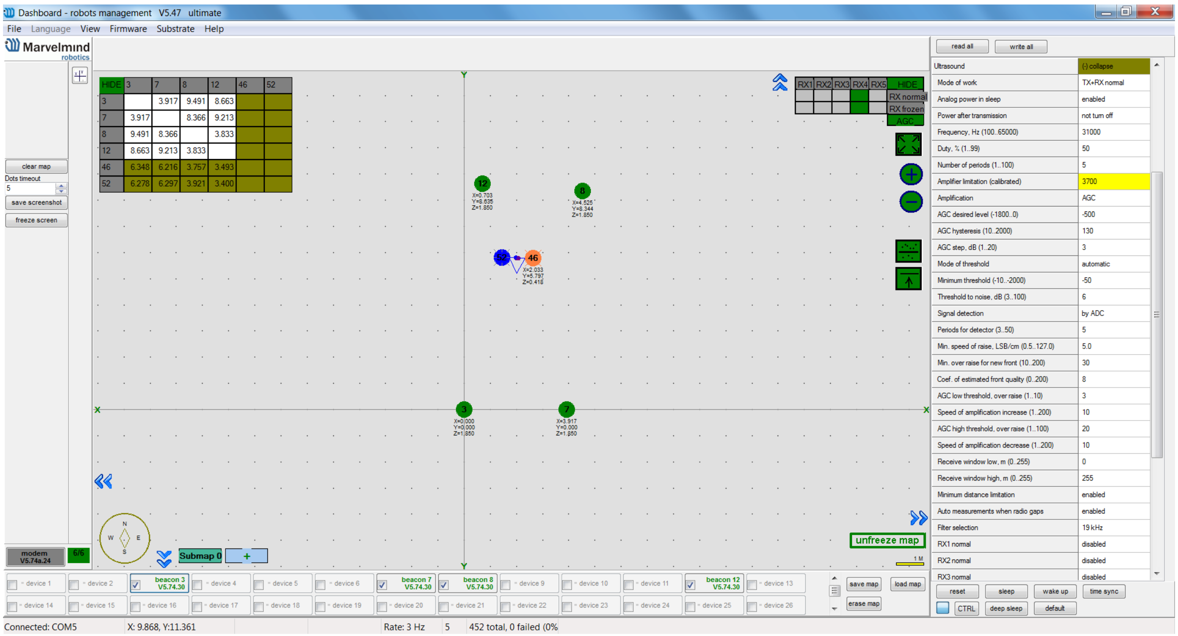

Figure 3: Dashboard configuration settings with only RX4 ultrasonic sensors active in each stationay beacon

Figure 4: Received signal by mobile beacon 52 from stationary beacon 12 with only RX4 ultrasonic sensor active in each stationary beacon.