Internet of Drones towards Logistics 4.0

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Declaration

I declare that this document is an original work of my won authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

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Abstract

Logistics main focus is to ensure the material’s efficient flow. Warehouses are the places where products are consolidated in the supply chain and thus constitute a pivotal point in the material’s effective flow. Recently there is a desire for warehouse digitalization driven by reduction costs, need to improve service level and safety. Two of such technologies, driving the costs’ reduction in warehouses, are IoT and UAVs or drones.

Thus, in this dissertation, we present the design and evaluation through a business case of a prototype of a UAV RFID based system solution aimed to perform inventory management. The proposed design can be summarized as follow: an UHF RFID Reader is carried by a DJI Ryze Tello EDU drone that reads ALN-9662 item tags. The RFID reader is connected through a Wireless USB Adapter to a Raspberry Pi Zero. For safety concerns, the prototype was unable to be tested in a real warehouse environment. The alternative to simulate a real warehouse was to adapt a room so that it looked like a storage area with three corridors and four single deep pallet racking shelfs. The experiments and tests were conducted by exposing the drone to different scenarios within the room. In the experiments the total time that the system takes to perform the cycle counting was, on average 248,15 seconds. The autonomous system is capable of scanning the tags with 100% accuracy, identified misplaced items and update the warehouse database in near real time. The system has a great economic potential.

Keywords: UAV/Drone; IoT; RFID; Inventory Management; Cycle count; Business Case

Resumo

A logística tem como principal objetivo assegura o fluxo eficiente do inventário. Os armazéns são os locais onde os produtos são consolidados na cadeia de abastecimento e constituem assim um ponto fulcral no fluxo eficaz do inventário. Recentemente, existe um desejo de digitalização dos armazéns impulsionado pela redução de custos, necessidade de melhorar o nível de serviço e segurança. Duas dessas tecnologias, que impulsionam a redução dos custos nos armazéns são IoT e UAV ou drones.

Nesta dissertação, apresentamos a conceção e avaliação através de um business case, de um protótipo de um sistema baseado num UAV e RFID, com o objetivo de realizar a gestão do inventário. A conceção proposta pode ser resumida da seguinte forma: um leitor UHF RFID é transportado por um drone que lê etiquetas ALN-9662. O leitor RFID é ligado através de um USB a um Raspberry Pi Zero. Por segurança, o protótipo não pôde ser testado num armazém real. A alternativa para simular um armazém real, foi adaptar uma sala, de modo a parecer um armazém com três corredores e quatro prateleiras de uma profundidade. As experiências foram conduzidas, expondo o drone a diferentes cenários dentro da sala. Nas experiências, o tempo total que o sistema leva para realizar a contagem cíclica foi, em média, de 248,15 segundos. O sistema autónomo é capaz de ler as etiquetas com 100% de precisão, identificar itens mal colocados e atualizar a base de dados do armazém quase em tempo real. O sistema tem um grande potencial económico.

Palavras-Chave: UAV/Drone; IoT; RFID; Gestão de inventário; Contagens cíclicas; Business Case

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Acronyms

AGV – Automated Ground Vehicle

AR – Augmented reality

BiDi – BiDimensional

CAPEX – Capital Expenditure

CCTV – Closed-circuit television

CF – Cash Flow

CODP – Customer order decoupling

CPS – Cyber-physical System

EPC - Electronic Product Code

ERP – Enterprise Resource Planning

GDP – Gross Domestic Product

GTIN – Global Trade Item Number

HF RFID – High Frequency Radio Frequency IDentification

HTOL – Horizontal Take-Off Landing

ICT – Information and Communication Technology

IMU - Inertial Measurement Unit

IoD – Internet of Drones

IoE – Internet of Everything

IoP – Internet of People

IoT – Internet of Things

IRR – Internal Rate of Return

ITS – Intelligent Transportation System

KPI – Key Performance Indicator

LF RFID – Low Frequency Radio Frequency Identification

LIDAR – Light Detection and Ranging

LoS – Line-of-Sight

MAV - Micro air vehicle

NAV -Nano air vehicle

NLOS – Non-line-of-sight

NPV – Net Present Value

PAV - Pico air vehicle

OSHA – Occupational Safety and Health Administration

PV – Present Value

QR – Quick Response

RFID - Radio-Frequency Identification

ROI – Return on Investment

RPAS – Remotely Piloted Aerial System

RPAV – Remotely Piloted Aerial Vehicle

SD – Smart dusts

RSSI - Received Signal Strength Indication

SBC – Single-Board Computer

SDK - Software Development Kit

SKU – Stock Keeping Unit

SLAM – Simultaneous localization and mapping

SNR - Signal-to-noise ratio

SOAP – Size, Orientation, Angle, Placement

SUAS – Small unmanned Aircraft System

TMS – Transportation Management System

UAS – Unmanned Aircraft System

TPC – Transmission Control Protocol

UAV – Unmanned Aerial Vehicle

UHF - Ultra High Frequency

USB – Universal Serial Bus

UWB – Ultra-wide-and

VPS - Vision Positioning System

VTOL – Vertical Take-Off Landing

WMS – Warehouse Management System

µUAV – Micro Unmanned Air Vehicle

1. Introduction

This introductory chapter aims to clarify the motivation behind the use of Industry 4.0 technologies in logistics activities. In addition, section 1.2 presents the goals and expected contributions of this work. Finally, section 1.3 provides the structure of the developed work

1.1 Problem background and motivation

Logistics is the backbone of every business and is a fundamental sector for and of the economy. The logistics sector is far more than just providing access for people and business to innovative goods and services. Discussions with stakeholders and the Logistics Conference 2013 identified that EU logistics costs represent about 10-15% of the final value of products. This includes costs such as transportation and warehousing. As a matter of fact, logistics play a pivotal role in supporting macro-economic processes and the operations of markets, critical infrastructures and distribution to both business and consumers. In the EU alone, the transport and storage sector employ around 11 million persons, accounting for more than 5% of total employment [1] and almost 5% of GDP (Gross Domestic Product) [2].

Logistics concerns the management of material and information flows in business [3]. More specifically it encompasses the efficient planning and implementation of all kinds of products, services and information flow in the supply chain from the starting point to the end point to meet customers' needs. The two main elements of a logistics supply chain comprise the supply, production, distribution and reverse logistics chain [4,5]. While logistics operations remain crucial for transporting goods, they are not a revenue stream for companies and thus these operations are continuously receiving pressure to increase their efficiency. Lately this pressure it is increasing due to the overall sustainability challenges [6] and the demand for higher service levels. The latter concerns the omnichannel context where due to next-day deliveries and an increasing number of online delivery services, logistics operations must find a way to keep up with the consumers' needs, while maintaining cost effective operations.

This apparent trade-off (High Customer Service Level and Low Cost) has been a point of conversation among scholars and practitioners. At the centre of conversation sits a pivotal piece of the logistics operations: the warehouse. Inside the warehouse the necessity for lower levels of inventory increases the complexity of these trade-offs. The warehouse has the function of better match supply and demand and interconnect all the moving parts of the supply chain while operating these 3 trade-offs (High Customer Service Level, Low Cost and Lower Inventory) [7]. Therefore, the improvement of warehouse's operations can have a major impact on the value chain's KPIs (Key Performance Indicators).

As never seen before and in an incredibly high speed, recent technological innovations are challenging the notion that these 3 trade-offs are mutually exclusive conditions. This challenge alone is prompting organizations to look inside their operations and questioning themselves how about how these technologies can influence the current management principles [6]. Although some technologies have been adopted in some sectors like automotive, logistics stills a rough diamond. The commitment to higher service level and reduced costs of operations will sooner or later drive logistics players to adopt the technological evolvement seen in the past years, conducting an industrial revolution, commonly known as the fourth logistics revolution (Logistics 4.0).

Two of such technologies, driving the costs' reduction in warehouses, are Internet of Things (IoT) and Unmanned Aerial Vehicles (UAVs) or drones, which equipped with visual based navigation and sensors [8] can help to achieve near real-time warehouse inventory, a key requisite to achieving high efficiency across the supply chain. UAVs are off extremely use because in addition to performing repetitive and dangerous tasks, they can take advantage of one of the pillars off Logistics 4.0 which is to collect data dynamically from multiple locations while carrying these repetitive and dangerous tasks. In addition to this, UAVs will benefit immense from the evolution of Information and Communication Technologies (ICTs) observed in the last decade [9]. Despite the wide use of these technologies in logistics before such as Enterprise Resource Planning (ERP), Warehouse Management Systems (WMS), Transportation Management Systems (TMS), Intelligent Transportation Systems (ITS) [10], UAVs will revolutionize the efficiency of these systems because they will capture the real time information that will increase the decision-making efficiency of these ICT systems, making them more trustworthy and flexible.

The reduction in costs is inherent linked to higher profits but this causal effect may be a collateral damage while companies try to react to new ways of consumption, mainly in an omnichannel context. The adoption of this technology will capacitate logistics operations to respond to a higher service level required these days, such as next-day delivery. That said, it is of special interest to discover if the pressure to achieve higher service level can bring a reduction of costs as well. Chronically these two things have been seen as mutually exclusive conditions, but are they? It is in this context that the work developed in this master's thesis emerges.

Figure 1. 1 Warehouse Trade-Offs [7]

1.2 Objectives

A warehouse operation involves a wide variety of tasks that require interoperability and high level of cooperation between entities. Hence the radical application of technology in this context can be catastrophic. The main objective of the dissertation is to create a framework that grants companies with the opportunity to identify the benefits and costs that the implementation of drones in their warehouse operations can bring and hopefully accelerate the adoption of internet of drones towards Logistics 4.0.

Given the diversity and complexity of each warehouse's operations and in order to ensure that the objective is met, the first major step is to map which challenges and opportunities for warehouses are being imposed with the advent of the new revolution also known as Industry 4.0. Afterward and subsequently accompanied with a high depth study of the different drones' associated technologies and each drone's potential in a warehouse environment, it is intended to identify the highest potential use cases for the use of drones in warehouses, i.e., the activities that can be better perform by UAVs or drones. To support the highest potential use cases a business case should be built upon a cost benefit analysis for the use of this equipment. The dissertation will follow closely the development of a prototype drone, where joint definition of specifications and requirements will be done between the author and another student from the MSc in Telecommunications and Informatics. The prototype will be validated through implementation (ideally) in real conditions and use of simulation to test different scenarios. To keep better track of progress the following intermediate objectives have been defined:

- Portray and characterize logistics operations identifying their main challenges today and exploring a holistic view of collaboration between companies' current logistic operations and Industry 4.0 technologies;
- Clarify and understand the motivations for adoption of Industry 4.0's technologies in logistics, based on the current competitiveness and innovation scenario as companies evolve into the new industrial age;
- Understanding and analyzing the context in which UAVs/drones will be implemented as well as all the processes that will be influenced by it;
- Identification of the highest potential use cases for drone adoption in warehouses;
- Creation of a business case to sustain evidence in favor of the use of drones in warehouse environment;
- Design, implementation, and evaluation of an UAV RFID based system prototype for inventory management and inventory traceability;

- Application of the prototype to a case and to test different scenarios. The objective is to minimize the total costs of inventory management activities, by reducing the number of necessary resources, ensuring that operations support a certain Service Level.

1.3 Document structure

The present Project of Dissertation is divided into four major sections:

Chapter 1 – Introduction

Concerns the present chapter in where the reader is contextualized about the motivation and background for the use of drones towards Logistics 4.0. The Project Objectives are outlined and divided into intermediate objectives and the overall structured is presented.

Chapter 2 – Logistics 4.0 technologies implication in Warehouses

This chapter aim to clarify the motivations for the adoption of Industry 4.0's technologies in logistics by characterizing the evolution of logistics operations based on a literature review. The implications of Industry 4.0 in logistics is analysed in a chronologically way. Later the today's main challenges are identified and a path towards a Warehouse 4.0 is explored.

Chapter 3 - Drone Technology as part of Warehouse 4.0

Drones/UAVs are identified as an Industry 4.0's technology. Different type of drones and associated technologies are discussed. The highest potential use cases are identified and reviews on previous work related to the use of drones in warehouse applications and state of art technologies, are explored with focus on industrial inventory and traceability. The main elements of the business case are identified. Besides the costs and benefits, topics like security and sustainability are discussed. Emerging Business Models are further explored through a literature study and conceptual research.

Chapter 4 – Methodology

In this fourth chapter, the steps of the proposed methodology used during this dissertation cannot be described before having a clear understanding of what is the most promising activity for drone's adoption inside the inventory management landscape. To allow the readers of this work to reproduce the methodology, each of its steps are detailed, accordingly with the literature review of the previous chapter. This chapter heavily focus on the steps behind a development of a business case, in order to convince the top management team to invest on an UAV RFID based system for inventory and traceability.

Chapter 5 – Data treatment | UAV Implementation

This chapter explains the main data obtain by the student of Telecommunications and Informatics Engineering (METI). The data obtain via experiments and tests is latter used in the results section to build the business case. All the data presented in this chapter were obtained exposing the prototype to defined scenarios build in partnership with the the author and another student from METI. This system was used to test different scenarios. An overview of the environment where tests were done is presented. Additionally, all simplification strategies used, and necessary assumptions are also provided.

Chapter 6 – Results Discussion

In this chapter, the main results obtained by applying the data referred to in Chapter 5 to each step of the methodology proposed in Chapter 4 are presented. The results presented comprise the savings estimation, cost estimation and economic justification. This application is made considering the experiments presented and the limitations of the system.

Chapter 7 – Conclusions and Future Work

In this chapter, as the name implies, all conclusions taken from the implementation of the drone developed throughout this dissertation are stated, as well as the main limitations of the drone put into practice. The chapter ends with some future work suggestions, thus explaining how the work herein developed can be carried on in the future.

2. Logistics 4.0 technologies' implications in Warehouse

Some attribute the origin of the word "Logistic" to the Latin [11] from the combination of Logic (Logic) and Static (Latin), but until World War II the word was just that, a word. Logistics was a major part of the success of those known as winners. The winners started to see the full potential of Logistics and started to treat it as a scientific subject and that remain till today. With the advent of globalization in the 90's, companies started to recognize transportation as an important factor in terms of cost and timeliness, as this started to threaten their existence in the competitive landscape. As cost and time management consolidated themselves as competitive factors, companies were forced to integrate transportation systems as strategically important in order to maintain the efficiency of operations. The never-ending drive to maintain competitiveness created a field called Logistics Management and supply chain departments within companies were created. Recent developments in information and communication technology combined with automation paved way for new ways to increase competitiveness advantages. These technologies are transforming Logistics as we know, creating a new concept called Logistics 4.0.

In this chapter, we intent to focus the literature review on some of the key challenges that will need to be overcome in order to meet the requirements of Logistics 4.0 and Warehouse 4.0. The role of logistics in business operations and the role of warehouses in logistics are defined in section based on a literature review. Later in section 2.5, these concepts are linked to the development of ICT, Cyber-Physical System (CPS) and IoT, and the term Logistics 4.0 is defined. In Section 2.2 we introduce the Industry 4.0 concept and a brief overview of this new era is given. Section 2.3 presents the main components that make Industry 4.0 a technological revolution. In Section 2.4 we discuss its main enabling technologies and features. In section 2.6 in addition to the link to ICT, CPS and IoT, we discuss the main implications and the basis of an efficient and solid Warehouse 4.0. As the trend for less human involvement in repetitive and automatic activities continue, we end this chapter with some conclusions in section 2.7.

2.1 Logistics and Warehouse

Logistics management is that part of supply chain management that plans, implements, and controls the efficiency, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the consumption point in order to meet customers' requirements [12]. In fact, logistics integrate different chains all with different characteristics and challenges mainly, supply, production, distribution and reverse logistics chain. When we talk about logistics supply chain, we need to take into consideration all the above chains and understand its complexity before designing or making any management decision upon each chain.

In a typical chain, production centers purchase raw materials from suppliers to convert them into finished products. Therefore, in this environment, production logistics includes the logistical processes within a manufacturing environment [13]. The focus of production logistics is to ensure high delivery capability and reliability of finished goods. The planning is highly affected by the point where production is based on specific customers' orders called customer order decoupling point (CODP) [14].

As production centers finished the transformation of raw materials into finished products, these finished products are transported to warehouses and from these to distribution centers that sell them to point of sale where they are purchased by the final consumer [15]. Supply chain management as a matter of fact strives for achieving coordination between all these entities that form the supply chain actors [3]. In doing so, the result is the delivery of high customer service level with cost effective operations between all the actors in the supply chain.

Recently logistics management have become more responsible for its disposing products, components or even the packaging of the products. Reserve logistics addresses exactly that by recycling, remanufacturing, repairing and managing products at the end-of-life to increase the sustainability of the industry [16].

The current challenges in the area of logistics include managing inventory more efficiently, delivering more frequently and smaller orders, have a high depth of Stock Keeping Units (SKUs) and increasing the value-added services available to the customer. These challenges are related in certain part to digital technologies that have led to a customer-oriented and individualized supply chain and logistics [17]. When overcome, these challenges can enable a better logistics performance. To better understand how these challenges, relate to performance we need to address what affect logistics performance.

Logistics performance is affected by two factors: structure and control issues [5]. The structure of logistics is related to the design part of the operations. It details how supply chain actors should be designed. As for control issues, these describe the day-to-day operations and how to execute them. The main focus is to ensure the material's efficient flow, while coordinating transportation, storage and handling of goods. The two factors are related because these day-to-day operations must be planned accordingly with the established structure. Given the complexity of coordination between all the control's activities, information flow is critical to manage the flow of goods [4]. With the continuous increase of coordination of operations, information and communication technologies (ICTs) now constitute the backbone of every logistics operation. Although companies have several options of transport [18], the choice depends on the delivery time and cost of the mode of transportation. In addition, these factors depend on the market and product characteristics. Furthermore, the delivery time and cost also depend on ease to storage and ease to handle of these products. These deeply dependent decisions increase the need for the use of ICTs for better utilization of resources.

As discussed in [3] logistics must balance delivering time and lead time. In a context where a company have multiple plants and numerous points of sale, we could ship the finished products from plants directly to the point of sales but this is not feasible, due to the requirement that delivery time should be less than the lead time of production. This compels companies to consolidate the products somewhere along the logistics chain in order to complete this requirement. The place where products are consolidated is called a warehouse. Companies use warehouses between two elements of the supply chain that receives products and then ships out, assembled assortments as needed. Nowadays warehouses intermediate the flow of products in the supply chain and respond to their variability, consolidate products from different suppliers and add value through various services such as labelling [19]. The addition of warehouses created various advantages. Powered by an efficient ICT a warehouse can create efficiencies in transportation, because we focus on each link specifically. In addition, we can achieve efficiencies in inventory because we can hold inventory where it's needed and just as much as is needed. The other advantage is risk pooling. Companies can hold inventories in just one location rather than scattered across this network of companies. In the end the inclusion of warehouses increases logistics performance. It is more efficient; it reduces the risk and it provides the customer with better service.

Warehouses have three basic functions: movement, storage and information. These functions are sustained by several basic operations, that are carried out from the receipt of the finished product to its dispatch to customers. These operations can be grouped into receiving, storage, order picking and shipping [19]. Figure 2.1 shows how performance is related to overall structure/design and operations/control issues. Basic warehouse operations are also showed. The main interest of the dissertation is the use of particular technologies to improve Warehouse Operations and not Warehouse Structure, so for the rest of the project dissertation when the author refers to warehouse performance, he is referring to performance of warehouse operations.

Warehouses are meant to facilitate movement of products by receiving them, by transferring them across the warehouse, by picking them when they are needed it and by facilitating shipment. At the same time warehouse must be able to have an assortment of products in the warehouse available readily for when the customers want them. Storage may be shorter term or longer term in the case of less used items. Lastly, warehouses must have information, mainly information about inventory. Warehouse managers must keep track what, how much and when inventory is coming in, what inventory levels currently are in the warehouse and what, how much and when inventory is going out. The three key performance indicators (KPIs) are presented in Figure 1.1. A more detailed procedure of when an item arrives is given as follow based on [19]. An item arrives at the warehouse. At the reception the operator registers physically the item in the system where all the product is registered. At this stage the type, quantity and quality of the product is checked accordingly with the specifications of the order put in place for this item. Afterwards the item is directed to the storage area or put away area, closing the receiving process. The storage process begins. An operator is in charge of storing the item in the warehouse. In most cases a Warehouse Management System indicates the correct position of the item in the warehouse. After the operator physically place the product in the storage location the product remains in storage until he is required for dispatch (put-away). The storage method and position inside the warehouse can differ taking into account the product's characteristics, not only physical (area, volume and dimensions) but also in terms of rotation, popularity, handling requirements, value and preparation zone inside the warehouse. When the item is required for dispatch the order is picked, which consists of the selection and collection of the product from the shelf. In this process the operator assumes that the product removed from their storage position have the available quantity ordered and its current position is the correct one. That is not true all the time causing this operation to be one of the most time and resource consuming operation in the warehouse. Finally, when the order is picked the shipment begins. In the beginning the order that was picked goes by a verification phase. After this analysis the products are placed in containers suitable for their transport and all documents necessary for the transport must be prepared. Finally, the orders are put on outbound area where orders are loaded on trucks.

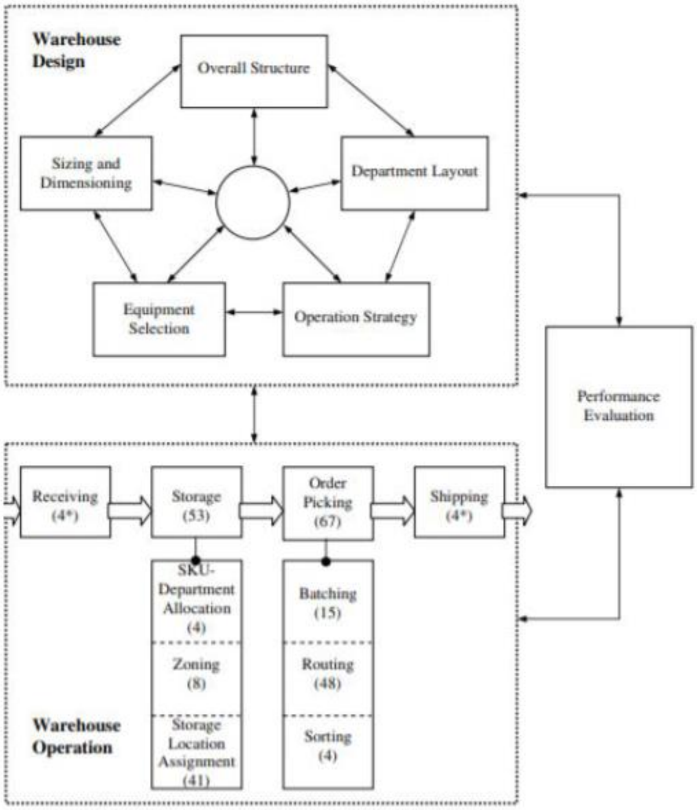


Figure 2. 1 Framework for warehouse design and operation problems [19]

Nowadays warehouses constitute one of the most important levels of the supply chain accounting for 30% of the total costs in logistics [20]. Recently these costs have been rising due to the need to shorten delivery times, increase high service level and the rise of the omni-channel retail strategy [21]. Lately, companies have been investing more in automation to address these ever- increasing costs. Moreover, companies have struggled to attract skilled labor. This amplified the problem, because the poor handling of goods sabotages the information flow, that is critical to effectively manage the flow of goods and inventory [4]. In particular, this poor handling affects storing and order-picking (the most time and resource consuming operation in the warehouse). Items misplace or in insufficient quantity will led to needless movement of goods, that will generate unnecessary costs in the form of excessive labor and increase the risk of products' damage. Information flow is critical for better utilization of warehousing resources.

As can be seen the lack of accuracy of the information flow, causes complex problems that affect the overall performance of warehouse operations. The use of IoT technologies and drones aims to solve some of these problems. The information flows are supported by information and communication technology (ICT) [22]. ICTs are in fact an enabler of information sharing but they rely on the accuracy of the data. ICT can increase the amount of information that companies are able to capture but if the information used is not according to real-time events, operations can be affected by it. Drones can enable access to a great deal of information in near real-time, enabling tracking and counting. With certainty of data accuracy drones can create effective information flows that will allow warehouse managers to better use warehousing resources

2.2 Industry 4.0 concept

The term of Industry 4.0 was first used in 2011 at Hannover Messe, in Germany as a basic concept for the fourth industrial revolution [23]. The terminology has used by the German government in a project to promote computerized manufacturing and since then has kindled public interest. Despite that Industry 4.0 is not perceived as the true revolution it is. Since 2011 this revolution has been coined by the rapid advances in digital technologies [24]. Recently the development and integration of innovative information and communication technologies in companies' operations have been notorious across several industries.

The first industrial revolution was the result of mechanization. Companies and governments used the harnessing of water and steam power to increase productivity of the iron and textile industries. In addition, it was the first-time humanity used heavy mechanical manufacturing equipment. The second industrial revolution was characterized by the use of electrical energy as a new energy source. This new energy source reduced manufacturing costs and allowed mass production. Electricity came in handy, as after WWI mass production was needed. Mass production were based on assembly lines that worked together with interchangeable parts. By using electricity in assembly lines, they could run by themselves, which led to increased productivity. The third industrial revolution was the result of the development of personal computers and the internet in the 80s, transforming the economic landscape [25]. Automation of production processes was then possible, through massive use of electronics in combination with information and communication technologies. Lastly, the fourth industrial revolution, builds on the third combining the virtual and physical world of production, machines, systems and sensors to communicate with each other, share information and to control each other independently. The evolvement of cyber technologies and their integration into digital ecosystems seems to be contributing for this revolution. It is expected that the result of combining information and communications technology with production and automation technology will bring even more innovation applications [26].

Since 2011 at Hannover Messe, many companies are exploring ways to create new and more efficient processes, services and products exploiting these Industry 4.0 technologies. According with McKinsey Global Institute, operations and equipment optimization in the factory setting can generate up to $3.7 Trillion of value by 2025 [27]. This came as no surprise as several other governments have launched similar initiatives as Germany. In Europe "Industry 4.0" is perceived as a new technology based on the Cyber-Physical System (CPS), where again the combination of physical and cybernetics systems is used to develop autonomous productive processes. In China the government coined the revolution "Made in China 2025" with the objective of upgrading the Chinese industry by 2025 by making manufacturing innovation-driven and emphasize quality over quantity. The Japanese government launched "Innovation 25" which is a long-term plan to promote economic growth by encouraging companies to embrace the changes created by globalization and the advance of digitization while trying to set the goals high and anticipating challenges for the future. As for the United States, several agencies coined this revolution "Smart Manufacturing", defining it as "a data intensive application of information technology at the shop- floor level and above to enable intelligent, efficient and responsive operations" [28].

Figure 2.2 summarizes the four industrial revolutions along the time scope.

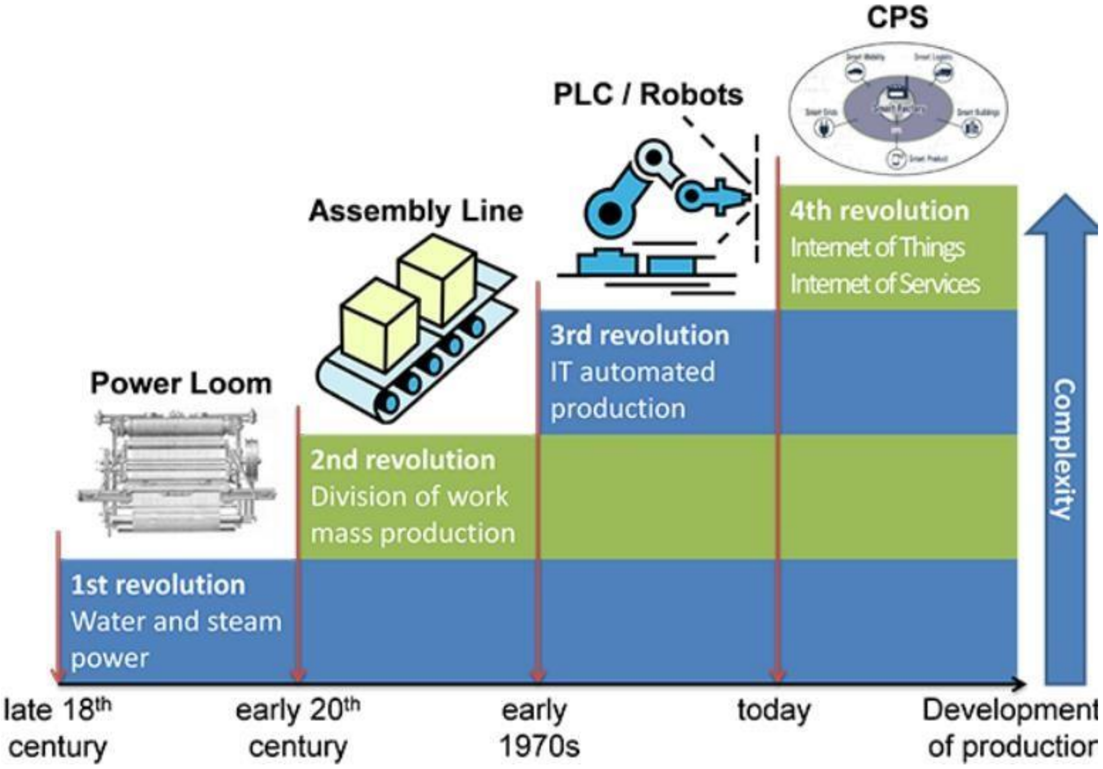


Figure 2. 2 Four Industrial Revolutions [29]

2.3 Industry 4.0 components

One can argue that the defining feature associated to Industry 4.0 is the intelligent networks based on cyber-physical systems [26]. What really differentiate this fourth revolution is the capacity of these technologies to leverage connectivity and communication among billions of devices [30]. The big difference is that these technologies can transform extensive real-time data into highly efficient decision-making, changing how humans and machines interact with each other.

In addition to CPS, Hermann et al. [31] identified more two components of Industry 4.0: Smart factory and The Internet of Things (IoT). The “Internet of Things” (IoT), also known as “Industrial Internet of Things” (IIoT) “allow “things” and ‘objects’, such as Radio-Frequency Identification (RFID), sensors, actuators, mobile phones, which, through unique addressing schemas, (…) interact with each other and cooperation with their neighboring ‘smart’ components, to reach common goals” [32]. This cooperation is possible because in IoT devices, all objects are interconnected and networked with each other.

This seemly fusion of the physical and virtual world was made possible by Cyber-physical systems (CPS), which are “integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.” [33]. These constants feedback loops between the physical and engineered systems and the computing and communication systems involves the interaction with a set of networked agents of IoT (Figure 2.3).

Figure 2.3 shows a third generation of CPS. They now can store and analyzed data and are equipped with multiple sensors and actuators with a full compatible network, but it was not always like that. The first generation only included identification technologies like RFID tags where storage and analytics were provided by a centralized service. Further developments brought CPS to a second generation. This second-generation CPS were equipped with sensors and actuators, but the range of functions were limited. The point of the fourth generation is to combine CPS and IoT to facilitate the integration of processes and systems across sectors and technologies. Closing the gap contributes to a better communication and collaboration with each other in a new intelligent way. IoT in fact, will affect the way CPS can collaborate, be controlled and managed.

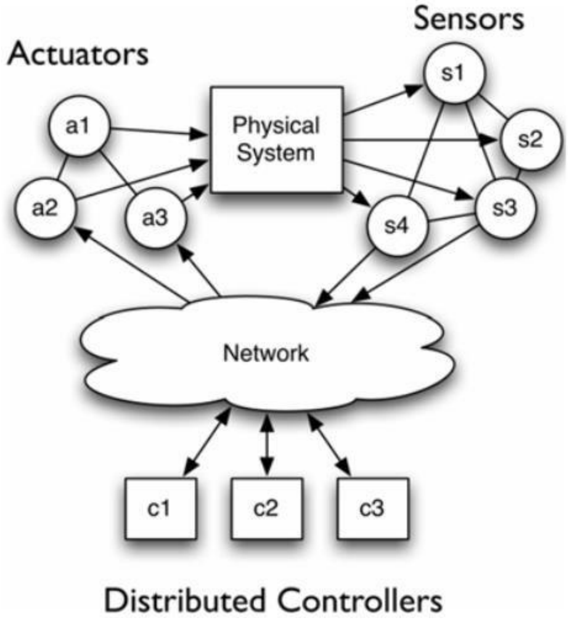


Figure 2. 3 General architecture of cyber physical systems [34]

Smart factories are the resulting idea of integrating IoT and CPS in companies' factory operations. "The Smart Factory is defined as a factory that context-aware assists people and machines in execution of their tasks. This is achieved by systems working in background. […] These systems accomplish their tasks based on information coming from physical and virtual world. Information of the physical world is e.g. position or condition of a tool, in contrast to information of the virtual world like electronic documents, drawings and simulation models. […]" [35].

Smart factories on the fourth industrial revolution resemble the idea of IoE (Internet of Everything) where machines, devices, sensors, and people are connected over the IoT and IoP (Internet of People) forming the IoE where new ways of organizing and conducting industrial processes emerge. To make IoE possible, the advance and incorporation of Industry 4.0 technologies should be smooth and in accordance with some features.

2.4 Industry 4.0 technologies and features

There is a selection of different technologies and concepts associated with Industry 4.0. Besides having a wide range of technologies under its umbrella, as a whole Industry 4.0 aim to create intelligent products, processes and procedures. We now provide a brief description of different technologies:

- **Identification** technology and **sensor** technology. These two technologies work together to recognize the identity of an object and acquire the near real-time data about it;
- Technology for **augmented** and **virtual reality (AR)**, that allow users to receive critical information in near real-time thus improving decision making;
- **Big data analytics** to make decisions based on tendencies given by the immense data available gathered via cameras or sensors. This information needs to be stored and processed in order to benefit from it. This process is responsibility of Big Data Technology. Blockchain can help to give security to these data. Blockchain is a distributed and secure ledger technology;
- **Advanced robotics** that take advantage of the advancements in fields such as communication, sensor and artificial intelligence to make robots smarter. These robots have evolved into faster, flexible and autonomous forces;
- **Additive manufacturing** (also known as 3-D printing) allowing companies to produce on-demand prototypes and personalized faster, cheaper and better products;
- **Networking technology**, where **IoT** is included, that allows connectivity between smart components and objects such as RFID which is an identification technology;

- **Artificial Intelligence** that mimics natural intelligence using computers to interpret external data, to learn from such data, and using those learnings to conduct descriptive, predictive or prescriptive analysis;
- **Cloud manufacturing** and **computing** to enable optimization of manufacturing resources and logistics;
- **Unmanned Aerial Vehicles** (UAVs), usually referred to as **drones**. These vehicles can be controlled remotely and can carry different sensors to record data, carry certain things or automated repetitive and dangerous tasks. Drones can be viewed as an element of the internet of things (internet of drones).

The reader is referred to [36] for a detailed description about automated **identification** systems and [37] in regards to **sensors** and **artificial intelligence** technologies, [38] for a comprehensive survey about **augmented reality**, [39] for a comprehensive discussion about **big data** and [40] for an discussion about the strengths and weaknesses of **Blockchain**. Furthermore, in an article published by OECD [24] it is explored solutions with **advanced robots**, for a deep understand of **autonomous robots**, the reader is advised to a Boston Consulting Group article [41]. Article [42] covers mass customization using **additive production** but the reader is recommended to article [43] to a deep dive on **3-D printing** technology. In order to get a comprehensive review on **network** technologies and especially **IoT** the reader is advised to [44], and [45,46] for more discussion on cloud manufacturing. Finally, the reader is referred to [47] for an extensive discussion about classifications, applications and design challenges of drones.

Technologies revolutions have been called revolutions in part because of the features they offer to industries. Industry 4.0 offers mainly four features: **interconnection**, **information transparency**, **decentralized decisions**, and **technical assistance** [31]. The **interconnection** or **interoperability** is enabled by IoT that allow “things” and ‘objects’, such as RFID, sensors, actuators, mobile phones, to interact with each other and cooperate with their neighboring ‘smart’ components. Recently, wireless communication technologies have played a role in increasing interactions between agents of the IoT [31]. These interconnected objects and people and the constant evolution of CPS enables a new form of **information transparency**. Information systems create a virtual copy of the physical world (this copy sometimes is called digital twins) by enriching digital plant models with sensor data [31]. This virtual copy ensures information transparency. Furthermore, the interoperability allows **decentralized decision-makers** to utilize near real-time information to make better decisions and increase overall productivity. Considering that information is transparent across all entities, cyber physical systems can make decisions on their own and perform their tasks autonomously [31]. Their embedded computers, sensors and actors allow for monitoring and controlling the physical world autonomously. This capacity allows humans to shift from machines’ operators towards strategic decision-makers and problem solvers. Given the complexity of CPS, humans need to be supported by **assistance systems**. These systems aggregate and visualize information comprehensively in order to make informed decisions and solve short notice problems [31]. In addition, Cyber physical systems can support humans by conducting automated repetitive and dangerous tasks.

The features of the Industry 4.0 are expected to cause a disruptive change for industry in the era of information technology. While this movement is certainly controversial since revolutions can never be proclaimed before they happen, the 4.0 industry concept is being transferred from industrial production applications to other fields such as Logistics 4.0. If some companies continue to invest in digitalization and integrating Industry 4.0 into their logistics operation this will have revolutionary implications of great proportions.

2.5 Logistics 4.0 era implications

From the time the term “Industry 4.0” was used by the German government to promote the computerization of manufacturing there were many companies that only focused on the use of fourth industrial revolution technologies on manufacturing applications without realizing that these technologies could be applied to the entire supply chain. In fact, recently, company executives realized that these technologies must be applied to the entire supply chain. The continuous applications of Industry 4.0 technologies in manufacturing have driven demand for high- individualized products and services. This customer-oriented operation supply chain demands a logistics operation that can be more responsive and flexible that can handle the changing environment which is extremely complex. As logistics concerns the management of material and information flows in business [3], while complexity continues to increase, traditional logistics operation doesn't seem to be up for the challenge. The tradition logistics operations seem to be outdated because they rely immense on human labour. This human labour being prone to mistakes usually undercut the accuracy of timely and correct information [14]. This lack of accuracy of information flows prevent logistics to cope with the high-tech environment observed in Industry 4.0. Fortunately, nowadays, companies are starting to notice that these challenges cannot be surpassed with ordinary planning and control practices [48] and are starting to apply the principles and technologies of "Industry 4.0" to logistics towards "Logistics 4.0".

The term "Logistics 4.0" is essentially the combination of using logistics with the technologies of "Industry 4.0" like CPS and IoT with everything they add. In this sense we consider that the analogy to define "Smart Factory", "Smart Products" and "Smart Services" can be used to define "Smart Logistics". Everything considered "Smart" in this context, whether it is factories, products or services, emphasizes the capacity to perform tasks that otherwise were performed by humans. These tasks normally are repetitive and dull. This takeover allows people to shift from machines' operators towards strategic decision-makers and problem solvers. In the case "Smart Logistics", i.e., logistics operations that have incorporated CPS and IoT, can address the lack of accuracy of timely and correct information, the Achilles' heel of traditional logistics. CPS and IoT can closely monitor and synchronize information from physical processes and actors to a cyber computational space and thus achieving accuracy of information flow across actors. Especially IoT can allow transmission of information in near real-time based on RFID tags [49]. The advancements of digitalization and automation has given us a time in which several opportunities for logistics improvement are now possible. The flexibility given by CPS and IoT make possible to be closer to the customer needs. As of right now the impact on logistics is currently tied to the state of technology but it is generally agreed that Logistics 4.0 will have a great impact on service level, overall optimization of production and a reduction on costs.

In the article [50], Logistics 4.0 which stands in a broader sense of Industry 4.0 includes five functional areas valid across businesses: data collection and processing, assistance systems, networking and integration, decentralization and service orientation, self-organization and autonomy. These functional areas are supported by the use of IoT that enables the communication between each other machines and humans in near real-time, promoting the interoperability, main feature of Industry 4.0.

As already stated in Section 2.1 the main focus of logistics is to ensure the material's efficient flow, while coordinating transportation, storage and handling of goods. Although this focus does not change with "Logistics 4.0", the key logistics activities' supporting cast is affected. Before the appearance of CPS or IoT, logistics operations already relied on technological applications commonly known as Information and Communication Technologies: Enterprise Resource Planning (ERP), Warehouse Management Systems (WMS), Transportation Management Systems (TMS), Intelligent Transportation Systems (ITS) and Information Security. In the new Logistics 4.0 environment the way ICT will fit in is of interested.

Article [14] cites some examples that can be used to describe the Logistics 4.0 environment:

1. Real-time big data analytics of vehicle, product and facilities locations can find optimal routing for material and product transportation;
2. On-site, on-demand, rapid manufacturing reduces the need for storing products.
3. In warehouses, autonomous robots and vehicles along with tracking and decision-making systems keep control over inventory;
4. Real-time exchange of information among different actors removes the traditional boundaries of logistics, which enables reduction in bullwhip effect;
5. Smart products and cloud-supported network keep the information flow intact.

This kind of environment proportionated by CPS and IoT technologies will boost overall efficiency of ICTs. The reader is referred to article [51] for a detailed analysis of how ICTs will be affected by Industry 4.0. Nevertheless, in an Industry Internet of things (IIoT) context, logistics operation requires, high need for transparency/visibility and integrity control (right products, at the right time, place, quantity, condition and at the right cost) of the supply chain [52], to be considered Logistics 4.0. To achieve that it is of extremely importance to study how Industry 4.0 technologies can help achieve that. Logistics 4.0 give opportunities to companies to transform logistics from simply a cost center into something that enables firms to compete on speed, reliability and cost, in other words, enable firms to leverage Industry 4.0 technologies to create a weapon of creation of economic and competitive value by transforming traditional Logistics into Logistics 4.0.

2.6 Warehouse 4.0

The Warehouses of different sizes, geographic locations, different nature of stored goods and different layouts are being highly transformed by Industry 4.0 worldwide. It seems no matter which is the function that a warehouse plays in the supply chain (consolidation or transit warehouse, cross- docking, sortation centers, fulfilment centers, etc) it is expected that a modern warehouse must be able to leverage Industry 4.0 technologies in their facilities.

Although warehouses have always been an integral part of the supply chain ensuring the flow of goods, this element of logistics was always perceived as a cost center. This is starting to change with the understanding of what it is smart factories, smart products, smart services and smart logistics. Some logistics providers are already seeing the movement of Warehouses 4.0 as opportunity to gain competitive advantages, rather than just a cost reduction movement [52]. The adoption of the Industry 4.0 features will certainty change how warehouse works, but maybe, more important, is the change that will bring in terms of how warehouses are perceived by warehouse and logistics managers.

According to a DHL report [52] this adjustment of perception and undergoing transformation of warehouses is the result of two driving trends. The first is related to a global shift to e-commerce and a revolution in customer expectations. The nature of fulfilments and distribution have become different, with single orders being much more frequent. This trend emphasizes a need for a warehouse which is highly agile, extensive, responsive and one that takes advantages of CPS technologies to optimize the capabilities of man and machine in a newly symbiotic relationship (IoE). Along with that, the report points out that the recent technology innovation particularly the advances in the physical/mechanical realm (Collaborative robotics, augmented reality, autonomous vehicles, sensor technology, drones and the Internet of Things), have helped to give birth to the Smart Warehouse or Warehouse 4.0. The “Smart Warehouse” alongside with “Smart Logistics” integrates new physical and analytical technologies like CPS and IoT in the traditional warehouse environment to transform operations, create economic and strategic value and eliminate the need for people to perform repetitive and dull activities, continuing that trend to move people from machines’ operators towards strategic decision-makers and problem solvers.

Making a remark about the lack of “smartness” of traditional warehouses certainly is an understatement. The efforts towards automation in the warehouse have been relevant in recent years but the new advances of IoT and CPS have dramatically increased the possibilities of success. Inside the warehouse, managers have been investing in technologies such as warehouse management systems, high-speed sortation systems, RFID, QR code, biometrics and closed-circuit television (CCTV), automated guided vehicles, pick-and-place robots, computer vision, networked sensors and mechanized picking systems for decades. Nevertheless, these forms of automation have limitations. The biggest limitation appears to be the lack of communication between robots and automated systems. The lack of communication weakens collaboration of systems, limiting the ways these tools could augment people and adapt to change. In addition, Automated Guided Vehicles require high capital investments, routine maintenance and repair. RFIDs in the other hand decreased flexibility of operations because they are not compatible with materials such as liquids and metals, are prone to interference and lack global standards.

Hence the emergence of Warehouse 4.0 is an emergent challenge, encompassing a smart warehouse developed with technologies that have flexibility at their core. Recent advances on Industry 4.0 technologies makes us believe that inventory counting can be reduced to hours instead of months, 100% inventory accuracy in near real-time is possible and overall safety of operations can be dramatically improved. Although scientific research just started recently, the technologies that seem to have the greatest potential inside the warehouse are AI solutions, to increase automation; IoT solutions, to boost communication and cooperation with ‘smart’ components; digital twins to ensure information transparency, a key feature of Industry 4.0; UAVs or drones that in combination with IoT can carry different sensors to record data for monitoring operations. These technologies can finally bring the “smartness” to the heart of warehouse operations while driving costs down.

The concept of “Warehouse 4.0” goes beyond cost cutting. Chronically warehouse managers have dealt with an apparently triangle of trade-offs involving warehouse operations, illustrated on Figure 1.1. Warehouse managers are proactively looking for digital technologies solutions with the intent of keeping operations running on low cost and lower inventory but with even better customer service level. In perspective for traditional warehouses this may be an ambiguous statement but for a Warehouse 4.0 it is not.

Warehouses 4.0 expect to achieve this goal by achieving 100% inventory accuracy, near real- time demand & supply insights while maintaining its facilities fully secure. It really seems that these underpinning technologies enable companies to do far more with less. Managers may not have to decide between increase throughput vs. reduced costs, increased pick rates vs. accuracy or inventory holding costs vs. cost of stock outs; instead they can have faster throughput with low cost, more productivity and efficient with lower levels of inventory and higher customer service level.

2.7 Chapter conclusions

This In this chapter, a focus was given to how elements of the fourth industrial revolution, also known as Industry 4.0 relates to logistics and warehouse, i.e., Logistics 4.0 and Warehouse 4.0 respectively. We addressed the key components that will need to be overcome in order to meet the requirements for a fully implementation of Industry 4.0: interconnection, information transparency, decentralized decisions, and technical assistance. Under the same principal components of Industry 4.0, Logistics 4.0 incorporate CPS and IoT technologies that can closely monitor and synchronize information from physical processes and actors to a cyber computational space and thus achieving accuracy of information flow. Thus Logistics 4.0 paradigm can be outlined as the optimization of logistics operations supported by integrations of computation and physical processes (Cyber-physical systems) that use relevant information, provided and shared though Internet of Things (IoT) systems, to make better and more informed autonomous decisions. In a technological perspective it must be noticed that the Logistics 4.0 paradigm is not to replace humans in their works but to use the tools of Industry 4.0 to augment people and adapt to change. In warehouses particularly these technologies will help to remove tedious and dangerous tasks allowing humans to shift to strategic decision-makers and problem solvers. In addition, these technologies avoid inaccuracies in warehouses, allow for better and faster processes and facilitate sharing of near real-time information in an effortless way. Therefore, the adoption of technologies towards Warehouse 4.0 contributes to a better communication and cooperation with each other in a new intelligent context, making room to incorporate customer needs in near real- time and enabling orders to be automatically filled in the right time, with the right quantity and in the right condition. In the next chapter we focus on how drones can be part of warehouse operations and what value they can bring to enhance efficiency of operations.

3. Drone/UAV Technology as part of Warehouse 4.0

The Fourth Industrial Revolution has paved the way for a world where smart warehouses will automate processes so that their operations could increase its productivity and efficiency. Despite their “smartness”, it is up to us humans, as strategic thinkers, to explore creative ways to implement the latest emerging technologies in warehousing activities. As we dive in on Chapter 3, we come full circle on the Warehouse 4.0 paradigm. In this chapter we applied the concepts of the Industry 4.0 to a specific use case technology: drones or UAVs. Of particular interest to this chapter is the brainstorming session that should culminate on how Unmanned Aerial Vehicles (UAVs) or drones can be implemented on warehouses to fully unlock their potential.

This chapter starts exactly by defining what are UAVs and drones in section 3.1. Furthermore, in this section the different types of drones are surveyed. A scrutiny about the suitability of the different types of drones in a warehouse environment is realized. In section 3.2 the momentous is carried over and the most promising areas of the use of indoor drone cases in warehouses are enumerated and ordered by highest potential for use in warehousing operations. In Section 3.3 we survey, with literature support, the previous work related to the use of drones in warehouse applications and the state of the art technologies with special focus on inventory and traceability technological solutions. Finally, we finished the chapter with business drivers for warehouses in section 3.4 and afterwards the chapter conclusions.

3.1 Drone/UAV: concept and types

The term ‘drone’ is already rooted in the collective psyche of people. Nonetheless, given that the word has become popular there is a multitude of other terms used to describe them. That multitude includes calling ‘drone’ a hobby aircraft that anybody can fly, but also to describe the high-tech weapons used by the military. So, as not to confuse the reader, the definition of drone and UAV goes as follow.

Drones essentially are flying robots which include unmanned air vehicles (UAVs) that fly outside and for a considerable number of hours and small drones that fly in confined spaces [47]. So essentially every UAV is a drone, but not every drone is a UAV. Even though for a strictly technological standpoint a drone is an unmanned aircraft that can fly autonomously, i.e., without human in control, it can actually be used to describe a wide variety of vehicles.

Drones often are classified based on different parameters including the size, flight endurance and capabilities of the vehicle and the field of application of the drone (civil, scientific or military). Nowadays, different types of drones evolved from the advancement in miniaturization of electronic components, such as sensors, microprocessors, batteries, and navigation systems [47]. These advancements gave rise to smart dusts (SD), which consists of many tiny micro-electro- mechanical systems including sensors or robots [47]. These SD are used in seafaring or land base autonomously vehicles that count under the given definition of drone. Despite the most common usage of the term ‘drone’ referring to an aircraft than can be remotely or autonomously guided, Fig. 3.1 show the spectrum of different types of drones. Between UAV, term that is often used as a synonym for drone, and smart dusts, there are various types of drones, which are called micro drones, such as micro unmanned air vehicle (μUAV), micro air vehicle (MAV), nano air vehicle (NAV), and pico air vehicle (PAV) [47].

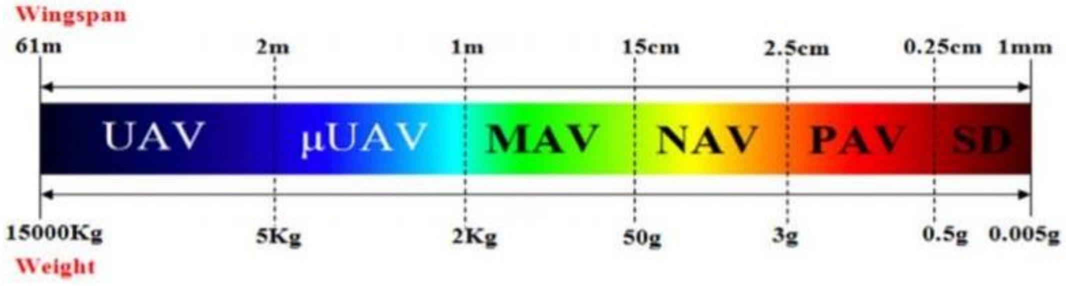


Figure 3. 1 Spectrum of drones from UAV to SD [47]

Unmanned Aerial Vehicles or UAVs are drones but they need to have autonomous flight capabilities, whereas drones do not. Therefore, all UAVs are drones but not vice versa.

The main interest of the dissertation is to study unmanned aircrafts and no other applications outside aviation; so, for the rest of the project dissertation when the author refers to drones or UAVs, he is referring to all spectrum of Fig. 3.1. If necessary, the terms µUAV, MAV, NAV, PAV and SD, will be used to discriminate the wingspan and weight of the drone.

In aviation and in space, the term drone refers to an Unmanned Aerial Vehicle (UAV) or unmanned aircraft systems (UASs). The difference between the two is that UASs includes not only the UAV but also the person on the ground [47]. UAVs can also be known as Unmanned Aircraft Vehicle System (UAVS), remotely piloted Aerial Vehicle (RPAV) or remotely piloted aircraft system (RPAS) and can still be called small unmanned aircraft system (SUAS). In spite of the huge use of drones in military actions, for this work it is more of interest the use of commercial UAVs.

There are four majors' types of UAVs: Multi-rotor drones, fixed-wing drones, single-rotor drones and fixed-wing hybrids.

Multi-rotor drones (or multicopters drones) are the most prevalent and most popular out of the bunch due to their sustainability, flexibility and affordability. This type of drones is mostly used by professionals and hobbyists in aerial photography, video surveillance and inspection. Multicopters can take off and land vertically and do not need runway for take-off. UAVs that can do this are considered vertical take-off landing (VTOL) UAVs, instead of horizontal take-off lading (HTOL) UAVs. Given that, multicopters are more efficient for hovering flight mode. This hovering flight mode consume a lot of energy considering that multicopters need retreating blades to fight gravity. In addition, these VTOL drones have limitations on load capacity and speed because of the stalling of these retreating blades. Due to this limitation HTOL UAVs are better equipped for longer range operations where cruise flight is needed [53]. Furthermore, this type of drone can also be classified based on how many motors they have. The Quadcopter is the most frequently used model being power efficient and having a great handling. This UAV has four electric motors that can adjust the speed at which motor spin. The spin is controlled by electronic speed controllers (ESC) that connect to a main computer board [54]. Tricopters are drones that can fly with less than four motors but have been proven to be very instable. Hexacopters have six rotors and provide a bit more power and ability to carry objects than the Quadcopters. Finally, we have Octacopters with eight rotors included. These eight rotors give this drone high raw power that can be applied to heavy lifting and others industrial applications.

Fixed wings drones often consist of the same elements of a normal airplane, a rigid wing, some kind of fuselage and tails which use a motor and propeller as their propulsion system [55]. This fixed wings drones can stay longer into the air as they do not need to use much energy to produce lift and beat gravity and similarly with planes they can glide in the air. This capacity allows fixed wings drones to cover larger areas in a shorter time. These drones usually are more lightweight than motor rotors, have low radar cross-section and are very difficult to detect [55]. As for disadvantages, these drones cannot fly in environments, such as urban or warehouses, because they do not have hovering flight mode and longer wings are quite delicate and likely to hit obstacles along the way. In the other end in cruise flight they can maintain motion for extended periods of time, especially if solar panels are installed on the wings.

Fixed-wing hybrids are a very interesting hybrid between the previous two as they can take off like regular drones yet engaged into gliding like fixed-wing drones while they reach a certain altitude or speed. This allows for improving battery limits while benefiting from the stillness and stability of rotor multi-rotor drones. At the moment it is a complex design mix and researches are experimenting different types of hybrid drones including tiltrotor, tilt-wing, tilt-body and ducted fan UAV [47].

Single-rotor drones or unmanned helicopters have a single rotor plus a tail rotor to control its heading [53]. They have a heavier payload capacity and have the ability to hover flight but come with the disadvantage of being more dangerous and harder to fly. Its larger rotor blade is a double- edged sword. Their large spinning blade offer a great efficiency but on the other side its complexity and vibration when working do not offer the security needed in close environments.

In **Table 3.1**, the pros and cons of each drone type are summarized.

Figure 3.1 and **Table 3.1** support deciding the size and the type of drone that represent the best choice for indoor applications in warehouses. Furthermore, for a more informed choice, the following points should be taken into consideration:

1. Indoor applications have less boundaries conditions compared to outdoor applications [57]: stable weather conditions, less hazardous tasks, less restrictive regulations and attractive investment costs;
2. Violating airspace, collision with birds and manned aircrafts, and flying in hazardous areas such as airports are not inhibitive factors for indoors [57];
3. Drones are expected to fly in tight corridors and the hovering area is limited as many obstacles are in the way;
4. Integration of drones into existing processes must be smooth;
5. Navigation based on GPS is not possible [57];
6. Drones are envisioned to work with humans so potential drone failures or battery explosions must be considered;
7. Drones must be able to carry extra support technology to perform tasks.

Regarding the size of drones, giving that warehouse aisle widths are not big, a **micro air vehicle** (MAV) or a **micro unmanned air vehicle** (µUAV) are the most appropriate for indoor applications. As for the type of the drone, **Multi-Rotor drones** and especially **Quadcopters** seem to have the highest potential for indoor applications. In opposition to octocopters a quadcopter offers a more efficient flight experience and it is more stable. Overall, this type of drone seems to have best fit with warehouse requirements and their weaknesses are mitigated by the indoor environment. For a drone to play a central role in the automation of current warehouse they have to have the ability to fly and hover corridors and aisles, have a structure that allow the avoidance of obstacles while keeping the ability to navigate indoor and operate in fleets using IoT technologies. Fixed-Wing drones do not offer VTOL or hover capacity and have a wingspan that does not allow indoor navigation. Single-rotor drones have VTOL and hover flight plus they can carry heavier payload which is great in comparison with multi-rotor. In the other end, single-rotor drones have to be able to work with humans under the same roof and form a symbiotic relationship. At this moment singe- rotor are too dangerous to work with people as they are harder to fly and too instable to a warehouse environment. Plus, they need a higher upfront investment. Fixed Wing Hybrid drones are not in perfect development right know and constitute a better use case for drone delivery rather than indoor applications. Multi-rotor seems to be the total package. They have a good price range, have VTOL and hover flight capacity, can operate in the limited aisles with safety and are easy to implement. This type of drones only has two disadvantages: short flight times and small payload capacity. There is an effort in drone technology development to mitigate these two things. Shorter flight times affect all the possible activities that drones can perform inside a warehouse, ranging from inventory management to intra-logistics. As for payload capacity this weakness will be as great as the dependence on this factor to perform warehouse activities. If we find out that the highest use cases for drone application on warehousing activities are not dependent on payload capacity, like inventory management or inspection, this may not even be a problem. In opposition if we find out that payload capacity is critical these may be a huge problem. Nevertheless, as drone's technology evolve this vehicle will be more capacitated to perform tasks that involve higher flight times and larger payloads.

Table 3. 1 Types of Drones: Pros and Cons (adapted from [56])

	Pros	Cons	Typical Uses	Price (€)
Multi Rotor	Accessibility Ease of use VTOL and hover flight Good camera control Can operate in a confined area	Short Flight times Small payload capacity	Aerial Photography and Video Aerial Inspection	€3k-€40k for pro drones
Fixed-Wing	Long endurance Large area coverage Fast flight speed	Launch and recovery needs a lot of space No VTOL/hover Harder to fly Expensive	Aerial Mapping, Pipeline and Power line inspection	€25k-€74k for pro drones
Single rotor	VTOL and hover flight Long endurance (with gas power) Heavier payload capability	More dangerous Harder to fly, more training needed Expensive	Aerial LIDAR laser scanning	€25k-185k for pro drones
Fixed-Wing Hybrid	VTOL and long-endurance	Not perfect at either hovering or forwardflight Still in development	Drone Delivery	TBD, in development

3.2 Drone/UAV Application on Warehouse 4.0 operations

UAVs have shown high potential and are considered a key technology for smart warehouses. They play a central role in driving revenue, profit margin and safety improvements in warehouse, since they collect data dynamically from multiple locations while carrying out repetitive and dangerous tasks in an autonomous way, such as [57]:

1. Inventory search and reconciliation;
2. Cycle counting and audits;
3. Roof inspection;
4. Security and surveillance;
5. Worker safety and productivity;
6. Item marking and recognition;
7. 2D/3D space optimization;
8. Empty and full slot detection;
9. Yard management;Forklift guidance;
10. In-warehousing transport;

This extensive list of tasks performed in a warehouse fall into three categories: Inventory Management, Intra-Logistics and Inspection & Surveillance. 2D/3D space optimization and Yard management does not fit in between the scope of the project as they refer to Warehouse Design (Fig 2.1). Before reviewing how come drones have found particularly applications in warehousing operations, we need to understand how drones can be incorporated with Industry 4.0 technologies and components [58].

Intelligent networks based on **cyber-physical systems** are the defining feature of Industry 4.0. **Drones** can fit in the general architecture of **CPS** (Fig. 2.3) in two different ways. Drones can be used as mobile sensors in the warehouse, since they have the ability to hover and fly autonomously all over the warehouse facilities easily, thus acquiring and transmitting data about processes (physical systems) [34,58]. As sensors, drones serve better for Inventory Management or Inspection & Surveillance. They would rely on the capacity to have higher flight times to perform these tasks more rapidly without stopping for a recharge. To do this, UAVs must use a scanner in order to read barcodes or other labelling technology, an identification technology and a connection to warehouse database to transmit data [59]. In addition, drones can be used as actuators, performing various physical operations. As actuators, drones serve better for intra- logistics. They would rely more on payload capacity to carry items across the warehouse. To do this, UAVs must use some form of self-positioning/mapping techniques to be able to follow pre- defined flight paths [59].

The integration of **drones** and the **Internet of Things** (**IoT**) has huge commercial potential. This integration allows the transformation of extensive near real-time data of CPS actors, into highly efficient autonomous decision-making. This integration also called Internet of Drones (IoD) is an essential step towards a smart warehouse or Warehouse 4.0. In this combination, drones perform like sensor platforms to acquire the near real-time data. Thus, this combination finds its most promising applications in the inventory management realm. Although, these applications share a common need for both navigation and airspace management [60]. IoD can provide such foundation for all current and future applications in the inventory management realm. IoD can be defined as an architecture designed for providing coordinated access to controlled airspace for unmanned aerial vehicles (UAVs), often referred to as drones [60]. IoD can be considering a cloud computing technology when combined with drones. Basically, drones become connect to the Internet, becoming a cloud infrastructure. Inside that infrastructure, cloud-based web applications provide real-time flight monitoring and management for drones. IoD is the architecture design behind the web application.

Given the possibility by **drones** to gather a huge amount of data via cameras or sensors, warehouse managers should look to **Big Data technologies**. These technologies could store and process all the data coming from drones, giving the ability to explore data driven solutions [39] in warehouses. These data-driven solutions can be applied to inventory management. If this technology and the insights it gives can be integrated horizontally (so that manufactures and suppliers can cooperate), the levels of inventory could be better managed and thus reducing costs and the bullwhip effect.

Integration of drones and Inspection & Surveillance are not yet fully explored but **3D printing** technologies [42] can be combined with **drones** [58] to maintain and repair warehouse’s infrastructures. Another alternative is the use of drones with **augmented reality** [38]. AR can equip drones to allow users to receive critical information in real-time video stream from the drone camera about the roof state [58]. In addition, this combination can be used to identify damaged products along the warehouse.

In short, drones can be used for inventory management for the following tasks: Inventory search and reconciliation, cycle counting and audits, item marking and recognition, empty and full slot detection (honeycombing) and take care of worker safety and productivity. Among them all, cycle counting seems to be the most time and resource consumption activity. Cycle counting describes the process of counting a partial amount of a warehouse’s inventory on a frequent basis [7]. This task is performed by physical verification of the quantity of items stored in the warehouse by a trained team of inventory control staff. They walk or drive to a designated location in the warehouse, scan the barcode of the item, count the units and move on to the next location following their schedule [7]. Cycle counting is designed to improve inventory accuracy and is performed daily or weekly [7]. This task and most of the above are laborious, tedious, risky, redundant and expensive. They require shutdowns, slowdowns, and downtime that result in lost revenue, inaccurate inventory counts, and harm or loss of life. It is for these reasons that drones are being explored in inventory management. Drones can act as mere sensors of CPS or can integrate

IoT and became smart drones. If the solution adopted does not include IoT, drones will act as flying sensors or mobile devices that gather data. In opposition when they are integrated with IoT they can became autonomous and became an essential part of inventory management giving their ability to communicate to a control system. In conclusion, smart drones will be used to automate tedious and dangerous tasks increasing safety for the workforce, increasing inventory accuracy and decrease labor costs. The field of intra-logistics does not offer the same potential use cases for drone applications as inventory management. Although drones can in fact act as actuators in CPS, the vehicle does not offer the flexibility of payload capacity it needs. Amazon states that about 83% of their packages weigh below 2.5 kg [61], a reasonable maximum payload for today's drones. Similarly, the average weight of packages delivered by FedEx is less than 5kg [62]. The ability to ramp up payload capacity will determine if drones can in fact act as an essential part of intra-logistics. Furthermore, to perform these tasks, drone technology has to evolve in order to solve the gripping/placing movements and navigation problems of contemporary drones [52].

Inventory Management applications appear to have the highest potential for use of Unmanned Aerial Vehicles (UAVs) or drones in warehousing operations.

The use of drones to replace manual inspection and surveillance seems to have potential. Drones can be equipped with inexpensive cameras and act as sensors in a CPS. In addition, drones can be equipped with AR to inspects roofs, racks, pallet placements, walls and ceilings [57]. This is of extreme high importance because as of late warehouse operations and customer demand makes inspection processes expensive and difficult, as this operation requires skilled inspectors [57]. Likewise, drones can serve as surveillance vehicles to prohibit theft. It is important to notice that the application in Inspection & Surveillance requires a higher flight time due to the requirements of these operations.

Table 3.2 summarizes the use cases for drone applications in warehouses. Inventory management seems to have the highest potential use cases with seven of the 12 use cases being in that category. The last column of the figure stands for the level of automation of drones in the respective warehouses. It is important to keep track of these levels as we go towards Warehouse 4.0.

As we dive deep in this section, it became clear that the most promising areas of indoor drone application are in inventory management followed by inspection & surveillance. Specially to perform tasks related to inventory management, the drone should have a high level of automation to be an essential part of smart warehouse. From now on, the dissertation concentrates its efforts to the use of drones for inventory management. In the next section we focus on the state of the art of industrial inventory and traceability technologies.

Table 3. 2 Use Cases - Application of drones in warehouse operations [57]

Area	**Drone Partner**	**Industry Partner**	**Location, Year**	**Navigation**	**Status**	**Technological Readiness**	**Autonomous Level (0-5**
Inventory Management	PINC	Kenco Logistics	Us, 2016	Vision	In-use	Commercial	4-5
	Hardis Group	FM Logistics	Fr, 2016	Vision	In-use (x9)	Commercial	4-5
	Aeriu	IKEA Soroksár	H,2018	Human	Experimental	Prototype	2
	DroneScan	LF Logistics	SA, 2018	Human	Experimental	Market launch soon	1
	DeltaDrone	GEODIS	FR, 2017	Vision with AGV	Experimental	Unique prototype	3
	InventAIRy	Rigtering Logistik	DE, 2017	Vision	In-Use	Commercial	4-5
	Infinium Robotics	Bolloré Logistics	SG, 2017	Vision with AGV	In-Use	Commercial	4-5
Intra-Logistics	Ascending Techn, Intel	Audi	DE, 2015	Human	Future	Prototype	1
	Not given	Fraunhofer Institute (IML)	DE, 2016	Not given	Future	Prototype	1
	Not given	Walmart	US, 2017	Not given	Future	Patent	N/A
Inspection & Surveillance	Not given	Ford	UK, 2018	Human	Experimental	Prototype	0
	Vtrus	Not given	US, 2018	Vision	Experimental	Market launch soon	5

3.3 Drone/UAV in warehouses applications: State of Drone/UAV technology

Simply put, drones need to become smarter in order to keep product traceability and perform inventory management activities in warehouse environments. Considering that they cannot become smarter on their own, to achieve autonomy these drones have to have incorporated in themselves technologies that together can manage to make drones smarter. This smartness of the drone relies upon the state of drone associated technologies, but in particular to the challenges imposed by complex warehouse operations [58], such as:

1. The ability to detect and avoid traffic (cooperative and non-cooperative) and multiple types of obstacles;

2. Appropriate datalinks for command and control (the identification, allocation and protection);
3. Cyber resilience (in order to mitigate against theft or deliberate use of the drone);
4. Human factors, to manage the transition towards effective solutions regarding contingency and failure management;
5. High precision navigation

Although drones can become true intelligent machines that can process the gathered data at high speed and autonomously using Machine Learning, IoT and Big Data, this is not the reality yet.

To keep product traceability and obtain the inventory of a warehouse the drone needs to have four essential elements [59]:

1. A labelling technology: items need to be attached to tags or labels that are associated with a unique identifier and, in some cases, with additional information on the item;
2. An identification technology: the labels or tags attached to the items have to be read remotely to automate the inventory processes;
3. Supply management techniques: data gathering, processing and storing processes need to be efficient when handling a relevant number of information;
4. Indoor navigation algorithm.

3.3.1 Labelling and Identification Technologies

Labelling and Identification Technologies have evolved rapidly in the last year. In the beginning, labelling technologies were limited by reading distance and their need for Line-of-Sight (LoS) between the reader and the code itself. This is the case of barcodes and Quick Response (QR) or BiDimensional (BiDi) codes. In the case of barcodes, they are simply a visual representation of Global Trade Item Number (GTIN) codes [63]. Barcodes increased dramatically inventory speed in industrial scenarios but are increasingly becoming outdated mainly because barcode readers need LoS with the barcode label to a correct read and it can only be read at relatively short distances. In low capital infrastructures barcodes are still a viable choice because they are easy to read by a simpler software and a barcode label is very low cost. In the other hand, QR codes are a more technological evolutional solution. They can store more than 1800 characters that can be read with a simple smartphone camera with no problem. This feature helps the use of QR codes to keep an overall low cost of the inventory/traceability system. Likewise, QR codes only can be read at shorter distances but can be improved by the size of the QR marker. Although, the necessity for a label that could be read without LoS between the reader and the code gave rise to RFID labels [64].

These labels revolutionized identification technologies with labels that can be read at several tens of meters [65]. Nowadays, there are two types of RFID tags: passive and active tags. Passive tags do not depend on batteries for carrying out RFID communications while active tags have a battery. The presence of the battery manifests the huge differences between reading distances. The reading distances for passive tags does not exceed 20 meters while active tags can reach 100 meters in unobstructed environments. RFID tags have evolved towards more sophisticated solutions and can now store additional product's information and measure temperature [66], acceleration [67] or light [68].

The last technological evolution of identification tags are the so-called smart labels [69] (Fig.1 display the evolution until the appearance of smart labels).

Figure 3. 2 Technological evolution of identification tags [59]

These labels are called smart as they allow for industry 4.0 features such as, event detection [70], operator interactivity, a display for visual feedback, one or more communication technologies, positioning services or embed IoT sensors that collect environmental data that are relevant for the state of a product [59]. The most mature solution is the omi-ID's View smart label [71] that has display, flash memory storage, active and passive Ultra High Frequency RFID transceivers, and an infrared receiver for beacon-based positioning. The smart labels are significantly more complex and more expensive than RFID ones.

In the last years a wave of communication technologies has been invading labelling and identification technologies. Among those, it is noteworthy to refer Bluetooth Low Energy that already has IoT applications [72,73] since they transmit a signal that helps to locate and identified these tags. Wi-Fi devices have been explored by the Media Access Control (MAC) [74] along with devices based on ultrasounds, infrared communications and Ultra-wideband [75,76].

In Attachment 1 the main characteristics of the most relevant identification technologies for inventory and traceability applications are shown.

Analyzing the technologies in the table and considering that these technologies are going to be incorporated in every product in the warehouse, RFID solutions sound a more promising (highlighted in red). High frequency RFIDs when compared with Low frequency RFIDs seem a better option. Both technologies require no power, both have non-line-of-sight propagation (NLOS) and no need for battery and can be integrated with smart devices of Industry 4.0 but HF RFID allow for larger reading ranges. This is specific important if we think on security purposes. In LF RFID the drone would have to be as close as 10 cm to read the label which can be very dangerous. Overall **HF RFID** look like the best option for warehouse sensorization.

3.3.2 Supply management techniques

Drones act as sensors that allow access to a great deal of information in near real-time. While this can allow tracking and counting, without good supply management techniques to handle huge data, warehouse managers cannot extract knowledge information about this data. Big data analytics can help extract that knowledge and improve decision-making in inventory and inventory management applications. This information is stored and processed by Big Data analytics, in order to benefit from it. Furthermore, Big Data analytics can communicate with ICTs throw IoT. In these circumstances' ICTs will do better and more informed decisions.

The reader is referred to [77] to explore a big data analytics framework that processes the information collected from an RFID-enabled shop floor. The author creates different (KPIs) in order to evaluate different manufacturing objects. The main findings serve as inputs for decision making actions. In addition to the advantages related to the performance of ICTs, the reader is referred to [39] to a deep discussion on the advantages of big data analytics for inventory applications.

3.3.3 Indoor navigation techniques

After analyzing the State of the Art, it was clear that the big challenge for the use of drones in warehouses, in a technology standpoint, was the accuracy of indoor navigation. Aeriu and DroneScan are experimenting right now this type of navigation where a human is coordinating the drone, but if we want to proper address the challenges Logistics 4.0 is bringing us there must be high level of automation in the indoor navigation department. Without that, companies still facing human error combined with lack of accuracy and consequently delays on their operation. Thus, fly automation it is a priority to withdraw the maximum potential of drones in warehouse operations.

Vision based or so-called SLAM (Simultaneous localization and mapping) algorithms provide a promising way to achieve 100% accuracy. The technologies available now are SLAM, Ultrawide- Band (UWB), radio frequency and light detection and ranging (LiDAR). One of the most advanced visual SLAM algorithms achieves an accuracy of 5cm, the radio frequency-based technology, often used to track floor conveyors (forklifts or pallet trucks) achieved an accuracy of 10-30cm and the LiDAR technology have shown proper results.

The technology ‘Aibot’ [78] achieved an accuracy of 2,5cm over an area of 10ha. This drone utilizes a combination of LiDAR sensors and cameras, measuring distances to a target by illuminating the target with pulsed laser light.

The company Vitrus [79] created a technology that combines 3D depth sensors and 3D scanner with 360° wide-angle cameras to achieve the highest possible accuracy. Their vision based simultaneous localization and mapping algorithm (SLAM) is processing millions of camera pixels in parallel, as often as 30 times per second. In addition, they are able to reproduce a 3D map and locate the drone inside the map.

There are other solutions. PINCs solution [80] is not only able to check inventory but also to localize it. These drones use hydrogen fuel cells, enabling them to fly for up to two hours – four times as long as some battery-powered drones [81]. InventAIRy [82] states that their software is capable of vision-based inspection providing information on packaging quality, pallet quality and possible damages on goods.

All these solutions have one thing in common: they want to master the challenge of indoor navigation. To implement drone in warehouse operations there must be an algorithm to overcome this challenge. In the bare minimum this solution must be accurate and autonomous to operate in an indoor environment.

Although there are alternative solutions like Geodis/DeltaDrone [83] and Infinium Robotics [84] that combine drones with an automated ground vehicle (an AGV) with a mounted calibration board on top. The tethered (wired) drones are physically attached with a cable to a ground vehicle, which also increases battery lifetime. Therefore, the airtime of such a technology is up to four hours, whereas technologies without automated ground vehicle can be up to ca. 30 minutes (e.g. inventAIRy). Yet, using wired drones reduces the hovering and manoeuvrability of drones and makes the integration in warehouses rather difficult.

Alternatively, to labelling and identification technologies, the choice of the Indoor navigation system is not so straightforward. This UAV’s specification will have to be done between the author and another student from the MSc in Telecommunications and Informatics.

3.3.4 UAV-based inventory systems

In the literature few papers detail the use of UAV for inventory and traceability applications. The majority of them are academic solutions and the few commercial applications do not use RFID as the identification technology embedded in the UAVs. Table 3.2 details some commercial applications, but the main features of their UAV based inventory systems is not public available. Nevertheless, Attachment 2 shows the most UAV-based inventory systems.

The literature review made it possible to reach the conclusion that although UAV have been a studied topic towards Warehouse 4.0, there is few detailed UAV for inventory management especially with RFID technologies. This realization highlights the scientific importance that motivate the dissertation.

3.4 Business Drivers for Drone/UAV adoption in Warehouses

3.4.1 Business Case for adoption | Project evaluation tools

The Throughout this project dissertation, especially in section 3.2, a great deal of explanatory arguments has been given in favour of the adoption of drones in warehousing operations, more specifically in inventory management where UAV can perform automatable and tedious tasks. Despite all that, integration of drones has certain costs that should be weighted. Is specially important to recognize if drone adoption will bring significant improvements of warehouse operations.

Admitting that the analysis done in section 3.2 was done in rightful way, this is not enough to get top management to invest in such technology without some due diligence. After being identified the most promising areas of indoor drone use cases in warehouses, a business case must be built to help understand which are the costs and benefits of drones' adoption in such tasks. Drones bring qualitative and quantitative benefits and qualitative and quantitative costs. Qualitative aspects should be included in a descriptive way in the business case while quantitative benefits should be used as a criterion for accepting or rejecting a project.

The main criteria for accepting or rejecting a project are the Net Present Value (NPV), Payback Rule, Internal Rate of Return (IRR) or Return on Investment (ROI). The first two are the most used.

The NPV can be defined as the Total Present Value (PV) of future Cash Flows (CFs) minus the initial investment

The PV tells us how much a future sum of money is worth today, given a specified rate of return. CFs can be costs (negative) or income and savings gained from the investment (positive). The letter *n* is the planned time horizon of the project and the *r* is the rate of return. The minimum acceptance criteria is NPV >= 0.

The Payback period is the estimated amount of time (np) for cash inflows to recover an initial investment (P) plus a stated rate of return (r). The Payback period analysis should be used as an initial screening tool, rather than the primary method to justify a project. This is because np neglects cash flows after payback and if r = 0% it neglects time value of money. Nevertheless, this tool is useful to sense economic risk in a project.

Is worth nothing the public and private projects have different characteristics. A public investment normally has a large size of investment, a longer project time (~ 30 years), there funding came from taxes, fees or bonds and they have to leverage different multiple selection criteria. In the other end, private investment as a small to medium investment depending on the size of the company, a shorter project life (2 to 25 years maximum), their annual Cash Flow is profit-driven and their primary selection criteria is ROI.

3.4.2 Benefits and Cost of Drone Adoption in Warehouses

The benefits of adoption of drones in warehouse operations have been discussed along this project dissertation. Drones can be use as strategic tools to create economic and social value tools that could augment people in the workplace. The major benefits will come from the ability of drones to act as sensors for data gathering that will allow, with integration with IoT, the transformation of extensive near real-time data into highly efficient autonomous decision-making. The main benefits of using drones are as follows [58]:

1. Unique capability to capture aerial data;
2. Ability to deliver rapid and seamless data collection;
3. Capacity for action in hazardous areas;
4. Easy access to difficult areas such as electricity grids, power station chimneys, etc.;
5. Autonomous navigation, without need for human interaction regarding the ongoing management of their trajectories;
6. Simple integration with other systems, by using the Industry 4.0 principle of Modularity

Furthermore, the main benefits for warehouse applications are as follow:

1. Autonomously navigation through warehouses to perform pre-defined paths;
2. Detect, identify and locate spots with honeycombing;

3. Keep product traceability.
4. Assurance of available quantity and correct position of product to picking;
5. Elimination of tedious and dangerous tasks, such as cycle counting;
6. Automatically uploads of resulting scans to the cloud via IoT and synchronization of real data and WMS data.

In short, drone ensures inventory accuracy, reducing operational costs and improving employee safety in warehouses.

As for the cost of the technology, drones seem to have a low Capital Expenditure (CapEx). Drones have three types of components:

1. Electronics: flight controller, sensors, electronic speed controllers, collision avoidance sensors, receivers, and an antenna;
2. Technology: accessories and materials incorporated on the structure;
3. IT: programming software

The production of these elements are becoming really cheap with the advance of 3D printing multiple parts of drones can be printed [58], such as: propellers, frame Landing gear, landing gear, camera mounts, antenna holder, protective equipment (i.e. prop guards), remote casing and battery pack casing. Furthermore, as can be seen on Table 3.1, multi-rotor are very cheap options. As drone technology evolved these solutions will become even cheaper.

3.5 Chapter conclusions

In this chapter, a focus was given to how drones can help achieve smart warehouses. With this in mind, a literature revision was done with the objective of finding the best suitable type of drone for warehouses, the best associated technologies and the most promising areas of indoor drone use cases in warehouses. The literature review allows us to conclude that an μUAV or MAV multi- rotor drone is the best suitable option for warehousing activities. Furthermore, the most promising area for drone's adoption is inventory management and product traceability. To perform such tasks in an autonomous way, a drone should be equipped with four essential elements: a labelling and identification technology, a supply management system and an indoor navigation algorithm. The solution proposed utilizes a quadcopter equipped with RFID identification technology and big data technologies to store and process all the data gathered. Further discussions on the indoor identification algorithm should be conducted.

Finally, in the literature there is little to no evidence of the use of UAV RFID based systems for inventory and traceability, thus the scientific importance that motivates the dissertation was consolidated. A business case must be constructed to support evidences found.

4. Methodology

In this fourth chapter, the steps of the proposed methodology used during this dissertation cannot be described before having a clear understanding of what is the most promising activity for drone's adoption inside the inventory management landscape. To allow the readers of this work to reproduce the methodology, each of its steps are detailed, accordingly with the literature review of the previous chapter. This chapter heavily focus on the steps behind a development of a business case, in order to convince the top management team to invest on an UAV RFID based system for inventory and traceability.

The outcome of a great business case should highlight a good opportunity for the use of a certain technology applied to a certain use case. In the instance of this dissertation, although a great deal of explanatory arguments has been given in favor of the adoption of drones in warehousing operations, it is necessary to have a complete understanding of which use case have the highest potential for this adoption. That's the starting point of this dissertation's methodology. This first step is crucial to understanding the following phases of the methodology, because it dictates what the following steps look like. A diagram including the 8 steps of the methodology used in this dissertation can be consulted in Figure 4.1. The end result of following the methodology should be a business case creation.

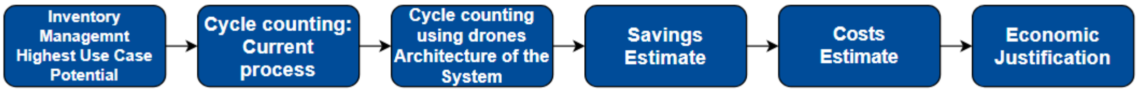


Figure 4. 1 Methodology used on the Business Case Development for the use of drones in warehouse activities

In the following sections, each of these steps are scrutinized in detail. In scrutinizing each step, it is intended to give to the readers of this work the bases of understanding in order to enable the application of this methodology to the particular cases of each warehouse. Lastly, as previously said, the reader needs to keep in mind that the first step will dictate the shape of the business case structure and the design of the UAV RFID based system to be developed by the student of METI.

4.1 Inventory Management Highest Use Case Potential

Usually the beginning of the development of a business case where a technology will be implement in a warehouse, starts with a deep understanding of how a specific technology works, how it supports the current activities of the warehouse and how these activities link to the overall company environment where the technology will be implement. In this dissertation that is not case. Drones, per say, are just flying robots. These flying robots need to be augment with complementary technologies to perform activities in the warehouse. One of the objectives of this dissertation is to design, implement and evaluate an UAV based system prototype. This prototype will be developed in joint venture between the author and another student from the MSc in Telecommunications and Informatics accordingly with some specifications. These specifications will vary a lot accordingly with the application chosen for the drone. Consequently, the complement technologies will also vary. Therefore, prior to study how a specific technology works, how it supports the current activities of the warehouse, it will be needed to discover the highest potential use case for inventory management activities inside a warehouse. Only this way, will it be possible to design a UAV based system prototype based on the findings. Upon that, the opportunities for improvement that arise with use of this system can be weighted in a business case.

To discover the highest potential use case for the use of drones in warehouses, several sources can be used. These sources are used as support, to match drones' capabilities with warehouse's activities characteristics. To construct a business case around this "match", it is necessary to use the **North Star Metric Framework.** This framework help to define a metric or leading indicator, that defines the relationship between the customer problems and the long-term business results. The reader is referred to [85] to explore a recently shared case study done by data scientists at LinkedIN about how improving a north star metric.

The list of tasks that can be perform autonomous by drones in a warehouse, fell in three categories: Inventory Management, Intra-Logistics, and Inspection & Surveillance. The necessary knowledge to decide which is the promising area of indoor drone application was obtained through literature review in section 3.2. The finding and respective north star (state of Drone Technology) are presented in the first layer of the North Star Metric Framework (Figure 4.2).

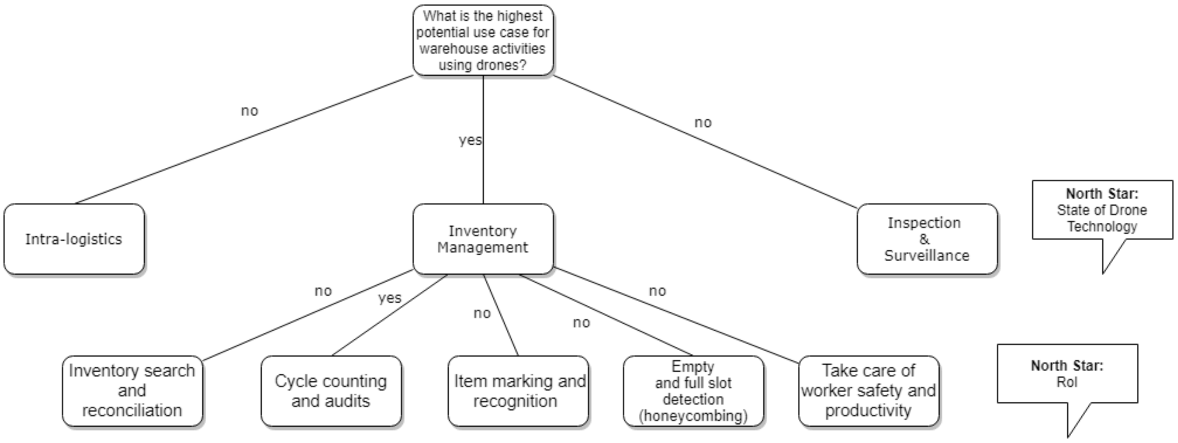


Figure 4. 2 North Star Metric Framework – "What is the highest potential use case for warehouse activities using drones?"

Despite the conclusion that Inventory Management applications seem to have the highest potential for the use of UAV in warehousing operations, drones can be used for numerous tasks. In section 3.2 the tasks numbered were: **Inventory search and reconciliation, cycle counting and audits, item marking and recognition, empty and full slot detection (honeycombing) and take care of worker safety and productivity**. Even though it was said that among them all, cycle counting seems the highest potential use case, this statement lacks arguments behind it. In order to enable the application of this methodology to particular cases, it is needed to construct a more robust argument using the **North Star Metric Framework**. The findings of this process constitute the second layer of Figure 4.2.

UAVs are an essential ingredient in the automation of warehouse activities. By augmenting the existing technologies adopted by warehouses, UAVs help improve the RoI on existing infrastructure. The RoI is the North Star Metric in this decision-making process. Nevertheless, the North Star Metric is impacted by **Input Metrics**. In this case these input metrics are divided into **two categories**: **ease of drone automation adoption** and **crave for cost effective operations.**

The first input metric it is related to how automation is progressing inside the warehouse. In other words, to implement automation, it is important to notice if it is easier to automate certain tasks than others, accordingly with their specific attributes.

The stages of automation were vastly studied. In the audit context, Vasarhelyi et al. [86], says that, human information processing and its evolution from man to machine is divided into four stages: 1) information acquisition; 2) information analysis; 3) decision selection, 4) action implementation. Vasarhelyi argues that ultimately it will be necessary to full reengineering the inventory management process. However, given that, to achieve completely inventory management automation, the system needs to handle enormous volume of data and real-time information across all entities, this full reengineering is not possible. Instead, this total reengineering has to be accomplished by incremental automation of manual steps in a methodically way, starting with tasks that are easy to automate regarding their attributes.

Based on the discussion in section 3.2 of the literature review, UAVs appear to show potential as mobile sensors in the warehouse, acquiring information and transmitting data about physical systems. Therefore, based on the four stages highlighted by Vasarhelyi, regarding automation of processes, drones are more suitable to operate in the first two stages: information acquisition and information analysis.

Issa et al. [87], categorized tasks as: routine manual, non-routine manual, routine cognitive and non-routine cognitive. Issa et al. clarifies that, “routine tasks require little judgement or thought processes, whereas cognitive tasks require thought and analysis. Routine tasks are repeated frequently with little or at least predictable variation whereas non-repetitive tasks may have variation and unpredictability”. Tasks that are considered to be manual routine are the simplest and most easily automated tasks. In contrast, the most difficult to automate are cognitive-non-repetitive tasks, as shown in Table 4.1.

Table 4. 1 The progression of automation in the context of task-type (adapted from [87])

Process Task Attributes	**Manual**	**Cognitive**
Routine	Easily automated	Moderately hard to automate
Non-Repetitive	Moderately hard to automate	Hard to automate

In short, regarding the first input metric, and keeping in mind that automation change should be incremental rather than disruptive, the tasks that are manual and routine should constitute the use cases where automation, using drones, presents the biggest ROI.

The second input metric is pretty straightforward. The crave for cost effective operations was a massive incentive for automation in the first place. In the inventory management realm a cost-effective operation is one which the tracking of the three main Inventory metrics (**Inventory Levels, Inventory Turnover, and Inventory Cycle Time**), is done in a way that consumes **less time and resources** [7]. In short, Inventory Levels are the numbers of items you in stock, Inventory Turnover is the ratio of how many times you sell the items in your inventory. This can be calculated for each part/product or for your total inventory and finally Inventory Cycle Time is how time it takes to fulfil a customer’s order. This can include manufacturing, shipping time, and other criteria [7]. These metrics can be track by a manual process or an automated process but regardless, every business which possess inventory, should track these basic metrics to make sure the business is running smoothly. In a manual process, to know at any given time what number of items a company has on the shelf, a manager needs to send people to count these items to know which are the inventory levels of which product, in order to know if they can fulfil orders. This process requires a lot of labor intensive activities. In an automated process all the metrics are elements that are being tracked dynamically.

In short, regarding the second input metric, the tasks that have the most impact, in terms of time and resource consumption, in regard to the three main inventory metrics, should constitute the use cases where automation, using drones, presents the biggest ROI. Table 4.2 compares each use case with the input metrics describes above.

Considering the analysis conducted on Table 4.2, of all activities, just two of them are subject of debate: Inventory search and reconciliation and cycle counting and audits. Both Inventory search and reconciliation, and cycle counting, relate to the process of comparing physical inventory counts with records of inventory on hand. As previous said cycle counting describes the process of counting a partial amount of a warehouse’s inventory on a frequent basis [7]. This task is performed by physical verification of the quantity of items stored in the warehouse by a trained team of inventory control staff. When every item listed on the rout is counted the cycle counting is done. Contrariwise the inventory search and reconciliation does not finish there. In the reconciliation phase in case there is a mismatch between physical inventory count and inventory management count, the company need to identify the root of the issue. To identify any discrepancies, one needs to look at the inventory deliveries/shipments since the last reconciliation. This can be done by looking for past delivery and sales records, see any math error or see if any stock number was misrecorded. After the root cause was founded, one needs to create a “stock reconciliation statement” that explains the discrepancies. Normally this last part is done by an inventory tracking system. These two activities have similar characteristics, mainly when we compare the inventory search with the cycle counting activity. Nevertheless, Table 4.2 show how they relate to the input metrics.

Table 4. 2. Relationship between input metrics and Inventory Management applications

	Routine	**Manual**	**Time and Resource Consumption**
Inventory search and reconciliation	Yes	Part manual Part automated	Inventory search is very labor intensive Reconciliation little labor intensive
Cycle counting and audits	Yes	Totally manual	Very labor intensive
Item marking and recognition	No	Part manual Part automated	Little labor intensive
Empty and full Slot detection	No	Totally manual	Very labor intensive
Worker safety and Producticity	Yes	Part manual Part automated Sometimes Informal	Little labor intensive

The highest potential use case for the use of drones in warehouses, is the one that suits the two-input metrics the best. In other words, the task to be automated by drones, should be a manual-routine activity which is a highly time and resource consumption activity. According with Table 4.2 and Figure 4.2, the highest potential use case for the use of drones in warehouses, is the cycle counting use case since it is the one where all metrics apply at full potential. Nevertheless, the other use cases should not be discarded, mainly because they have synergies between them. A UAV based system with the aim to perform cycle counting can perform other tasks while doing it. This possibility should be evaluated.

Next, we need to characterize the processes that occur in the cycle count, in order to identify the limitations of this process and thus list the improvements expected when this process is to be automated by drones. This characterization will also help to define the design the UAV based system prototype aimed to perform cycle counting.

4.2 Cycle counting: Divergences between current and future processes

This step on the methodology address the divergences between present and future processes of cycle counting. First off, it is necessary to characterize the current operation. After characterizing the processes that constitutes the cycle counting, we are in position to point out the limitations of these processes and thus conclude about the expected improvements. Describing the current processes will help us not only understand the current limitations of the process but also know which specifications of the process we should consider when building the UAV based system prototype. In order to proceed to the next step of the methodology, in the end of this section several things should be clear: processes that occur in the cycle count; limitations of the current cycle count operation; design of the UAV based system prototype aimed to perform cycle counting; expected processes of the future cycle count; expected improvements of the new process

4.2.1 Cycle counting: Current process

Any inventory of raw materials, finished goods, as well as intermediate in-process inventory has an economic value, and is considered as an asset in the book of the company [88]. Accordingly, any asset needs to be managed to ensure it is maintained properly and is stored in a secure environment to avoid pilferage or loss of thefts. Inventory control assumes significance on account of many factors [88]. First of all, inventory of raw materials, as well as finished goods can run in thousands of stock keeping units' varieties. Secondly, inventory can be in one location or spread over many locations. Thirdly, inventory may be with the company or may be under the custody of third-party logistics provider. These factors necessitate inventory maintenance mechanics to be devised to ensure inventory control. Inventory control is also required as an operational process requirement. Inventory has two different dimensions to it. On one level, it is physical and involves physical transactions and movement of inventory [88]. While on the other hand, inventory is recognizable by the book stock and the system stocks maintained. This necessitates an inventory control mechanism to be implemented to ensure the book stocks and the physical stocks match at all times. Thirdly, the inventory always moves through supply chain and goes through various transactions at various places [88]. Therefore, it becomes essential to control inventory and have visibility though the pipeline, including transit inventory. The financial managers will be bothered if the warehouse has too much inventory and the sales team will also be bothered if a warehouse has shortage of inventory that prevents fulfilling orders. In the other side the stakeholders want to know the profit and losses in a reliable way. In order to do that a warehouse manager has to make sure that inventory levels are accurate. There are two ways of doing that. Inventory control is exercised though inventory audits and cycle counts.

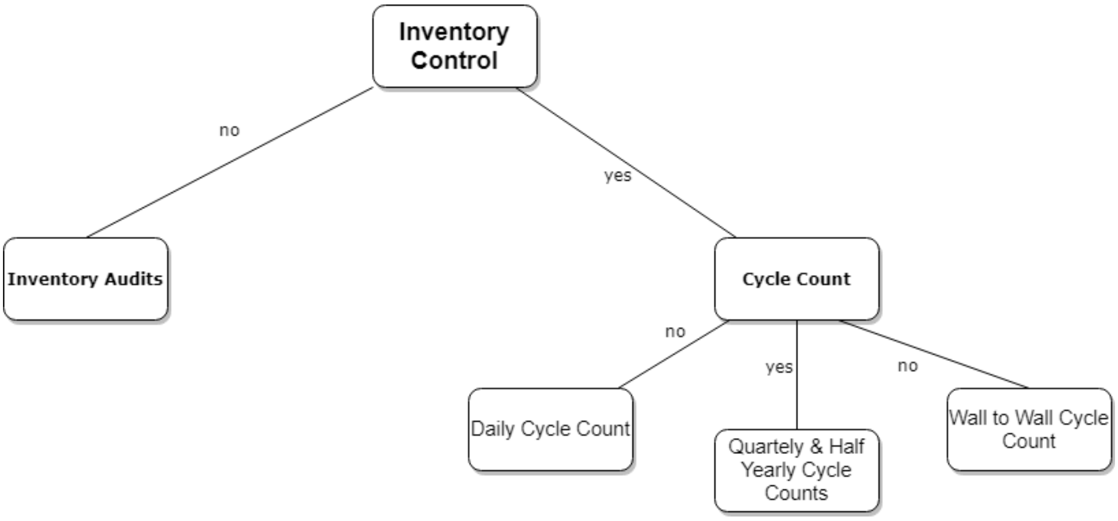


Figure 4. 3 Inventory Control (adapted from [88])

An inventory audit essentially comprises of auditing the books stocks and transactions and matching physical stocks with the book stock.

Cycle counts refers to the process of counting inventory items available in physical locations depending upon the nature of inventory, number of transactions and the value of items, cycle count can be carried on periodically or perpetually. Daily cycle count normally where the number of SKUs is very high, coupled with higher number of transactions and throughput. Daily cycle count is initiated where in a certain percentage of locations or SKUs are counted on daily basis and physical's stock is compared with system's stock. By the end of the month, all the stocks would have been covered once in cycle count. There are numerous ways of doing cycle count. Apart from daily cycle count, a warehouse can also perform Quarterly & Half Early Cycle Counts and Wall to Wall Cycle Counts. The last, mostly called full physical inventory, happens when the warehouse is stopped for a period of time and the warehouse's employees do an end-to-end physical inventory checking "wall-to-wall". System transactions are also frozen until the count is completed. This means lost sales up to two days that can be critical to some businesses. The inventory system throws up a count list with SKUs' number, description, and location number. The operator goes to the location, checks the SKU, counts the quantity available and updates the list, which is then fed into the system. The system reconciles the physical quantity with system quantity and throws up the discrepancy report, which is further worked upon to tally and adjust inventory.

There are four reasons to implement cycle counting [88] as a regular part of business' processes, namely: Improved service levels through focus on improved flow; It is more costly to address inventory discrepancies after they have had a negative impact on the warehouse's operation; Eliminate the need for wall to wall physical inventories; Measure accuracy of the company's inventory records.

Without accurate stock levels, effective inventory management is impossible, thus the need to implement a continuous event like cycle counting. With this procedure a warehouse manager should aim to a 2% to 3% tolerance level, meaning that the material in the warehouse at a given tieme, agrees with what is in the WMS system with no more than a 2% to 3% variance, both by the number of pieces, quantity and value. Cycle count program should deliver [88]: Uncover root causes of inventory discrepancies and eliminate or reduce future inventory discrepancies; Increase labor efficiency, improve product flow and customer service, by identifying early the discrepancies, prior to those impacting on the operations; Meet the requirements of the accounting department and external auditors for procedural controls; Provide appropriate tools, processes, and procedures; Educate the distribution team on the importance of having accurate inventory number; Provide the means to track and report compliance and performance against pre-defined key metrics; Allow for reductions in safety stock levels.

There are five cycle count strategies, meaning, five different ways to choose the products to count on any given day [88]: Geographic counts, Ranked-based counts, Random counts, Low Balance counts and Exception Counts.

Geographic Counts

A lot of accountants and auditors prefer this method. This is a wall to wall count where you start at one end of the warehouse and count a certain number of bins or items each day to get to the opposite end and then you repeat the process. The APICs organization recommends counting every item at least four times a year, this means that four times a years, warehouse's workers have to go through the entire warehouse, to count every item at least four times a year. Although this seems the best method for finding misplaced material because every square inch of the warehouse is checked, this proves to be not the most effective method. This method can be implemented by physical area as well, where we divide into sections based on physical space of department or product category.

Ranked-based Counts

Cycle counting based on product rank or ABC cycle counting is an alternatic to random counts. It used the Pareto's principle as the basis, which states that for many events, about 80% of the effects come from 20% of the causes. It is assumed that: 20% of the items in a warehouse are responsible for 80% of the sales and are the "A" items; "B" items represent 30% of the warehouse items and 15% of sales; "C" items correspond to 50% of warehouse items and 5% of sales.

In this method bins/items with a large number of transactions or hits are counted more often. Hits are a line in a pick ticket. If a customer asks for one, two or thousand of a product it is still one hit. Products with larger hits are more prone to errors because anytime someone goes to the bin to pull an order, is a chance for an error to occur. Those items that are most likely to be inaccurate need to be counted more often. Items with low hits, are the ones considered to be the most accurate inventory in the warehouse. There is no reason to count those items over and over again because this is dead stock that is sold once or twice a year. After sorting annual hits in descending order one can even go into detail and describe "C" items as 4% of sales, "D" items as 1% of sales and "X" items as "dead", that is, no activity within the previous 12 months. After the warehouse manager as this information, he/she can decide how many times to count each "A"," B","C","D" and "X" items per year. A example can be to count "A" items six times a year, "B" items twice a year and "C"," D" and "X" items only once a year.

Random Count

This method occurs in situations where a manager doesn't want the "cycle counters" to know in advance what is going to be counted on a given day. Random Counts are a "statistically valid" way of determining overall inventory accuracy but, this method is not going to be as effective because we are concentrating our efforts on those items that have the greatest chance of discrepancy. Although random counts can be implemented when random events like theft happen in a warehouse.

Low Balance Counts

Low balance counts are an option when there is labor shortage to conduct cycle counting, that is, there is no enough time to count all the products schedule in a given day. These methods consist on counting products when the on-hand quantity equals or falls below the minimum stock level. Because there is not much in the bin or pallet, it is going to be a faster count. This method is more effective than random count because faster moving items tend to be replenished frequently. In that case "A" items are counted more often than other items, using this method. This method should be implemented when people have trouble keeping up with the rank-based counts schedule or the warehouse have a shortage of labor at a given day.

Exception Counts

This method is designed to complement other cycle counts. Exception counts describes the process of counting items that you know have an obvious accuracy problem caused by an unexpected stockout, a negative on-hand quantity or continual inconsistencies between the perpetual inventory and the quantity counted. This process should be triggered on the day of any one of these problems occur. A suggested method could work as a combination of a rank counting method and an exception cycle counting where, simultaneously, we count products with a greater chance of error more often and immediately count problems with obvious perpetual inventory errors.

Most warehouses have coding systems at hand, where pickers already pick orders using radio frequency or "RF" bar coding equipment. Warehouse that already have this system, are in a far better position to cycle count in opposition to a traditional paper-based system. This requires some discipline in the warehouses. Every bin location must be bar coded with the bar-code id number. Bin location labels should be permanently attached as well. Either every piece of an item must be bar-coded, or a bar-code label must be placed on the bin identifying the stored item. Employees should be able to remove lite-id bar-code labels. Every time a picker remove material from a bin or palette and swipes the barcode, the WMS knows that material has been moved or has been sold.

Whatever method the manager chooses to implement in the warehouse, there should be a metric associated to the accuracy of inventory levels. In other words, a **tolerance level** for "how accurate is accurate" should be established.

Tolerance Level will vary with: Quantity maintained in inventory; How the product is counted; Value of the product; Subjective management decisions

How the product is maintained in inventory affects the tolerance level.

If the product is maintained in bulk for example, thousands upon thousands of pieces are inside a great bin. In that case it is difficult to do an accurate account as in opposition of having one or two pieces sitting on the shelf. It is not possible to count each piece physically when stored in bulk. In that case, normally, these products are counted by **weighing** a sample of the product. Then entire bin is weighted in order to get an estimate. This procedure means that you are not going to have as accurate inventory level because the scale is not proportionally, and the actual weight of each specific piece may vary a little bit. When the cycle count is based on weight, you should assume a **higher** tolerance.

In the other end, if the product stored is very **expensive**, each piece should be counted individually. The tolerance levels are subjective management decisions but, for this kind of valuable products the tolerance level should be very **low**. In addition, products with long lead times and/or order cycles should also have a **low** tolerance level.

Despite variations in the tolerance level, the *Material Management and Accounting System Standards for federal Contractors*, suggests an initial tolerance level of 5% of the quantiy or value or "x" dollars. This means that, the account quantities can be 5% high or low based on the actual quantity and still be considered to be an acceptable count. The products that are bellow this tolerance level will still be corrected in the WMS or computer records but will not appear in the list of exceptions

Planning of the Cycle Counting

A cycle counting program should be planned in order to know what to count and how to count products at any given day. The cycle counting procedure in a broader sense can be described by the following steps:

1. Complete data entry on all inventory transactions, so the inventory database is fully updated.
2. Print the report and assign it to the particular staff.
3. Location, quantities, and other details cited in the report will be compared with the items on the shelf.
4. Investigate if there are any differences.
5. Modify the process to alter the error if there are any.
6. Adjust the inventory record database to remove the error found by the cycle counter.

Before completing the second step, the warehouse manager should decide if the cycle counter will count bin locations or the effective number of products inside the warehouse. If the warehouse possesses a WMS that maintains on-hand quantities by bin location, the “cycle counter” knows that the company has “x” pieces of the product in one bin and “y” pieces of the same product in a different bin. Counting by bin locations highly increase the productivity of the cycle count activity. Otherwise if “cycle counters” just know the total quantity of an item that is stored in the warehouse, he/she needs to count all bin locations for that specific item at the same time. Figure 4.4 helps to illustrate that.

Oftentimes the same product is stored in several different locations inside the warehouse and those locations can be far away from each other’s. In the diagram bellow the product A100 is stored in three different places in the warehouse. If we maintained on-hand quantities by bin location, we could count those in three separate counts. In effect we are counting them as three separate items because, we are keeping track of the quantity in each location. If we only have one quantity in our WMS, we are forced to count product A100 in all of those locations at the same time. In this example, the “cycle counter” needed to go to each corner of the warehouse just to count item A100. That said, counting by bin locations is more effective than counting per quantity.

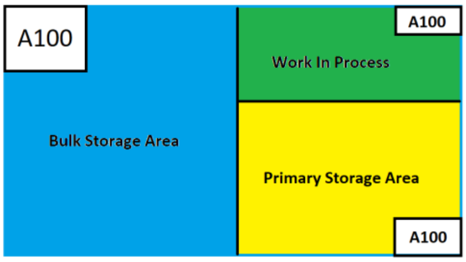


Figure 4. 4 Products are often stored in more than one location

A successful third step implies that the warehouse manager already decided how many products and what products the “cycle counters” should count in that day. Both what and how many products should the “cycle counter” count depend on the cycle count strategy used.

Geographic Counts:

To compute the number of products that are counted per day in the Geographic Count:

$$\#ProductsPerDay = \frac{Number\ of\ Bins\ \times Annual\ Counts}{Number\ of\ Days\ Available\ to\ Count} \quad (1)$$

If we imagine that a warehouse has 10,000 bin locations, and keeping in mind that the APICs organization recommends counting every item at least four times a year, this means that on 250 business days do to cycle count:

$$\#ProductsPerDay = \frac{10{,}000\ Bins \times 4\ Counts}{250\ Days} = 160\ Products\ Per\ Day$$

Ranked-based Count

In the same warehouse, with the same 250 business days, this cycle count strategy will result in very different products counted. Considering the reasoning of where was established that 20% of the items in a warehouse that are responsible for 80% of the sales and are the so called “A” items, we can build a Table 4.3

Table 4. 3 Rank-based count

Rank	# Bins	Times to Count	Total Counts
A	2,000	6	12,000
B	3,000	3	9,000
C	4,000	2	8,000
D	1,000	1	1,000
Total	10,000	-	30,000

In this strategy a warehouse manager can choose to count “A” items six times a year, “B” items three times a year, “C” items twice a year and ” D” items not even one time because this is “dead” stock with no transactions last year. Applying the expression (1), with the total of 30,000 counts divided by the 250 Days, we have to count 120 bins per day:

$$\frac{30{,}000}{250\ Days} = 120\ Bins\ Counted\ Per\ Day$$

In this method we are going to have much more accurate inventories level with less effort than the Geographic or Random Counts. We can combine the Geographic or Rank-based system and form cycle count groups. In that way, a cycle count group contains a reasonable number of items to count within a session.

These strategies are theorical in way because they do not consider several factors that will define how many products a warehouse realistically can count per day. The actual number of counts will depend on various factors, including: How many people are available to cycle count? ; How much time is available to cycle count? ; Time necessary to count each product ; Is data entry and analysis help available?

The first question is really key, because it is of extreme importance that experienced employees are the ones doing the cycle count. These employees already know the products very well, thus they are going to be accurate and accomplish this task faster. The avoid time constraints, the cycle counting should normally be done before or after the busiest working hours, when there is little or no material movement. The penultimate factor relates to the variance of difficulty of counting a specific product. This will vary by the type of product. Products that are har to handle are going to take more time to count than other products. Lastly, in addition to the people counting, we need to have people available to help with data entry. These people need to be available to analyse the count, identify the discrepancies and helping correct these discrepancies

In the fourth step, cycle counters are walking with count sheets in their possession to investigate if there are any differences. The first column in the count sheet, is always the list of items each counter is to count on a specific day. Another information on the count sheet can include batch and control numbers;

item and unit of measure; bin location; lot/serial numbers (if applicable); quantity to find (optional). One example could be illustrated in Table 4.4.

Table 4. 4 Example of a Physical Count Sheet

Physical Count Sheet							
Warehouse Lisbon					**Batch 12734412**		
Control Number	**Item**	**Unit of Measure**	**Bin**	**Lot**	**Serial**	**Qty to Find**	**Count**
19887766	A100	Box	A-02-05-09			198	
19887767	A234	Each	A-03-04-10			254	
19887768	B475	Box	A-06-03-08	W2156		142	
19887769	C120	Each	A-02-03-10	W2158		21	

Batch and Control Numbers

A batch number is assigned to each count sheet to ensure the counts are completed and updated in the perpetual inventory system or WMS. A control number is assigned to each bin/item combination to ensure that every bin is counted. The two numbers are used in parallel to make sure that all items have been entered properly in the computer system.

Item and Unit of Measure

It is very important to associate items with their unit of measure. The unit of measure is used for situation where there are boxes of product on the shelf. These boxes contain one, two, three or more pieces of the actual product. It that cases we used unit of measure to know whether the WMS system is maintaining pieces or boxes because the cycle counter needs to know what unit of measure they are counting exactly. In the example above the right unit of measure should be explicit between one box or four pieces of the product.

Lot and Serial Numbers

Lot numbers are assigned to a specific “batch” of a product, not to an individual item). If a product is maintained in the WMS system by lot number, the count sheet must list a separate line for each bin/item/lot number combination. This is of extremely important when we are talking about products that have expiration dates associated. Assigning a lot number to a batch allows the cycle counter to prioritize the batches that are close to the expiration date. Serial numbers in the other hand, are assigned to specific units of a product. If a product is maintained in the perpetual inventory system by serial number, the count sheet must list a separate line for each bin/item/serial number combination.

Shelf Quantity to Find

The quantity to find does not equal the on-hand quantity represented on the WMS. It depends on when the on-hand quantity is updated in the system. There are three ways to update the on-hand quantity:

- The on-hand quantity is updated when material is removed from the shelf (e.g. RF Bar Coding System).
- The on-hand quantity is updated before the material is removed from the shelf (e.g. as pick tickets are issued).
- The on-hand quantity is updated after all the material on an order is gathered or processed (also known as a “backflush” system)

It is important to know how inventory is updated in the WMS because otherwise the quantity on the shelf may disagree with the on-hand quantity in the WMS. Preferably, the cycle count happens after working hours (end of each day or the beginning of the following day). The Shelf Quantity is the quantity the "cycle counter" should find on the shelf. To determine the shelf quantity, we must distinguish between **Immediate** and **Future Committed Quantities**. Immediate Quantities are committed quantities that will be filled today (sales order, transfer order, work in process orders). Future quantities are quantities that will not be filled today. Therefore, typically, the shelf quantity is going to be the on-hand quantity minus the immediate committed quantity.

Although the first 3 steps are super labor intensive, the most difficult part in the counting process is not actual counting it is analysing the count. Analysing the count comprises looking at discrepancies. Discrepancies are the significant differences between the quantity contended and the quantity that should have been on the shelf. A report should list bin/items whose counted quantity differences exceed the accepted tolerance level:

$$[(Shelf\ Qty - Qty\ Counted) \div Shelf\ Qty] \geq Tolerance\ Level \tag{2}$$

OR

$$[(Value\ of\ the\ Shelf\ Qty - Value\ of\ Qty\ Counted) \div Value\ of\ Shelf\ Qty] \geq Tolerance\ Level \tag{3}$$

This calculation can be done automatically by the WMS to see if a specific product is within tolerance. The representations of this computation using expression (2), are presented in Table 4.5. In this case we consider a tolerance level of 5% per recommendation of the *Material Management and Accounting System Standards for federal Contractors.*

Table 4. 5 WMS Computations to see if count fall within the Tolerance Level

Item	Perpetual Inventory	Cycle Count	Difference (%)	Within Tolerance
A100	100	91	9.0%	No
A234	55	54	1.8%	Yes
B475	18	16	11.1%	No
C120	24	31	29.2%	No

Only A234 was within tolerance. The WMS will still be updated with the number of the cycle count but a research to know why the difference was of one piece will not be conducted. The other items will be part of the Discrepancy Report. A good discrepancy report in a WMS will not only show the discrepancies but also the transactions inside the warehouse. If these transactions relate to Immediate Quantities, they can easily identify the reason between the discrepancy between quantity contended and the quantity that should have been on the shelf. For this to happen the report must always list bin/item combinations that exceed the tolerance level and open transactions for those products. The objective is that the discrepancy report will identify both bad counts and data input errors. Upon that, the fifth and sixth step of the cycle count can be performed. The cycle counting procedure is finished.

Now that all stages of the cycle counting procedure were characterize, we are in position to identify the limitations of this process. The three main limitations of this process fall into three categories: very intensive-dangerous labor activity, time to perform the activity and lack of accuracy on discrepancies reports.

The first deductive analysis is that this task is very demanding physically. Sadly, at this moment, this task is performed by physical verification of the quantity of items stored in the warehouse by a trained team of experienced inventory control staff. This creates a conflict of interest, where experienced staff at the ones doing the very demanding work physically rather than problem-solving work. No matter the cycle counting strategy that the warehouse manager uses, "cycle counters" have to walk or drive to a designated location in the warehouse, scan the barcode of the item, count the units and move on to the next location following their schedule. For the higher shelfs they have to get help from existing equipment. This procedure should be repeat by "cycle counters", each day of the week. By the raw nature of the work, this task is laborious, tedious, risky, redundant, and expensive.

Secondly, as seen by the example where we applied expression (1), this processes takes a long time each day. Apart from that, this all work result in only counting "A" items 6 times a year. These items are the ones where turnover is very high and inventory levels could change daily and very rapidly. That said, they are only counted 6 times a year and require a lot of work to do so. To do just one cycle count, where all products "A" are counted, we are looking to a schedule of months. At the end of the month, we may be analyzing records that are completely different than the real-time information on inventory levels.

Thirdly, this operation seems to be outdated because to perform the cycle count, managers rely immense on human labor. This human labor being prone to mistakes usually undercut the accuracy of timely and correct information. In that case, the management team should carefully review every item appearing on the discrepancy report. In fact, there will be items that have discrepancies because of human error. Common reasons for discrepancies, where the quantity in the WMS does not agree with what is on the shelf include: Transactions for the item have not been properly recorded.; Wrong quantity taken to fill an order; Wrong product taken to fill an order; Product filled from different bin; Stock placed in wrong bin; UOM misinterpreted; Data Entry Error; Damaged Material.

These causes are arbitrary and may be the result of tiredness of the labor force or related to the dull nature of the job.

This subsection supplied the necessary knowledge for the design of an UAV based system prototype presented in the next subsection. After charactering the processes that make the cycle counting and respective limitations, it is possible to conclude on the reasons for the adoption of automation in warehouse operations using drones. In the next subsection, a design of an UAV based system is proposed. The design of the system proposed allow us to imagine a new way of doing cycle counting using drones. This exercise will help us, later in the methodology, to identify the opportunities for improvement of the operation.

4.2.2 Cycle counting using drones | Architecture of the System

To perform cycle counting inside the warehouse the UAV based system has to have **four** main components incorporate, namely: **Inventorying component, navigation component, communications component, and a local database.** Each component uses one or more associate technologies that perform the desire requirements. These technologies can be described as [59]:

1. A labelling technology: items need to be attached to tags or labels that are associated with a unique identifier and, in some cases, with additional information on the item.
2. An identification technology: the labels or tags attached to the items have to be read remotely to automate the inventory processes.
3. Warehouse management system: the drone needs to communicate to a WMS. This system needs to be efficient when handling a relevant number of data information.
4. Indoor navigation algorithm.

Section 3.3 of this dissertation provides an extensive literature review of each technology.

According with information collected on Section 4.2.1, about what a cycle count program should deliver and the typical steps of the cycle count procedure, the UAV RFID based system prototype should meet the following requirements:

- The system must be able to scan the labelling technology attached to the item, be it a tag or a label. Mandatorily, the system, need to collect the information associated from these tags, whether they are in line-of-sight or obstructed by either another item or farther inwards on the shelf.
- The labelling technology should be affordable in bulk and ideally reprogrammable, and it should be easy to put on the items.
- To issue discrepancies reports, the system should identify misplaced items in the shelfs.

- Ensure that drone hardware and software both have collision avoidance capabilities in order to work alongside operators doing other operations simultaneous.
- Don’t be dependent on human labor. We want the system to be as autonomous as possible.
- The system needs to communicate with the WMS, in order to keep inventory levels updated in near-real time. Consequently, the connection between the drone and the computational platform should have the minimum amount of downtime possible.

The prototype to be developed between the author and another student from METI (Guilherme Portela), is a **proof of concept.** The two dissertations have different scopes. The requirements stated above were build together in order to be possible to build the prototype. Although the software and hardware will be built by the student of METI, the collected information on 4.2.1 were important to define the structure of the proof of concept. The goal of this dissertation is to use the results of the prototype build by the student of METI and applied them to a business case.

Figure 4.5 portray the **proposed communications architecture**. In such an architecture, a UAV carries a Single-Board Computer (SBC) or computational platform and a tag reader. The SBC is attached to the drone and communicate with him by wireless communications. Furthermore, the SBC is connected to the tag reader by a Universal Serial Bus (USB). The tag reader is used for collecting data from item tags attached to the items stored in a warehouse. These tags have the correspondent information of the item. The SBC has a local storage that is used to collect tag data from the tag reader. Then, the SBC processes the data and updates the warehouse database periodically, through wireless. The SBC not only updates the warehouse database with tag information, but with the drone’s position as well, through a reliable transport layer protocol such as Transmission Control Protocol (TPC).

In this architecture, the UAV is a vehicle for the SBC and the Tag reader. The SBC provides the UAV with the indoor navigation algorithm, perform the inventorying activities with the help of the tag reader and aggregates the information between each subsystem. Thus, the software inside the SBC forms the backbone for the smart drone. In short, the system overall, perform like a sensor platform that aims to acquire the near real-time data. In such system, the drone is just a vehicle. In fact, is the SBC that guides the drone across the warehouse and collect and processes the data with the help from the Tag reader.

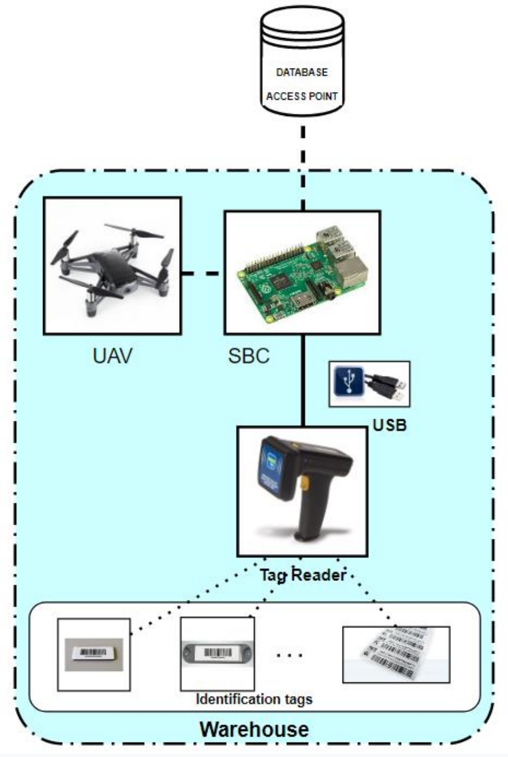


Figure 4. 5 Proposed communications architecture (adapted from [59])

As previously said, the UAV based system has to have **four** main components incorporate, namely: **Inventorying component, navigation component, communications component, and a local database.** Figure 4.6 clarifies how they interact with each other. It is important to define the four components build the student of METI to better understand the implications in the business case.

Interpreting the figure bellow, we can see that the communications component (green colour in the figure) sits in the middle of the system and communicates directly with the local storage and with the Warehouse database. There are two types of information that this component is communicating to the warehouse database. The first kind of information is related to the right side of the picture, in yellow. At the bottom right, the tag reader installed in the drone collect data from tags (Inventorying Sensors). Then, the role of the Inventorying Component, is to receives this data and update Local Item Table accordingly. The left side of the figure (blue colour) relates to other kind of information. The sensors installed in the drone collect data about the position of the drone (Navigation Sensing). With that information the navigation component feeds and update the Local Node Table. Additionally, the component computes the route that the drone should take next and assess, based on the information of the Navigation Sensing, if the drone is following the correct path. The local storage stores the information of both components: A Node Table and an Item Table. These four components work in parallel to make sure that the information gathered by the sensors of both sides is updated in the warehouse database in near real time.

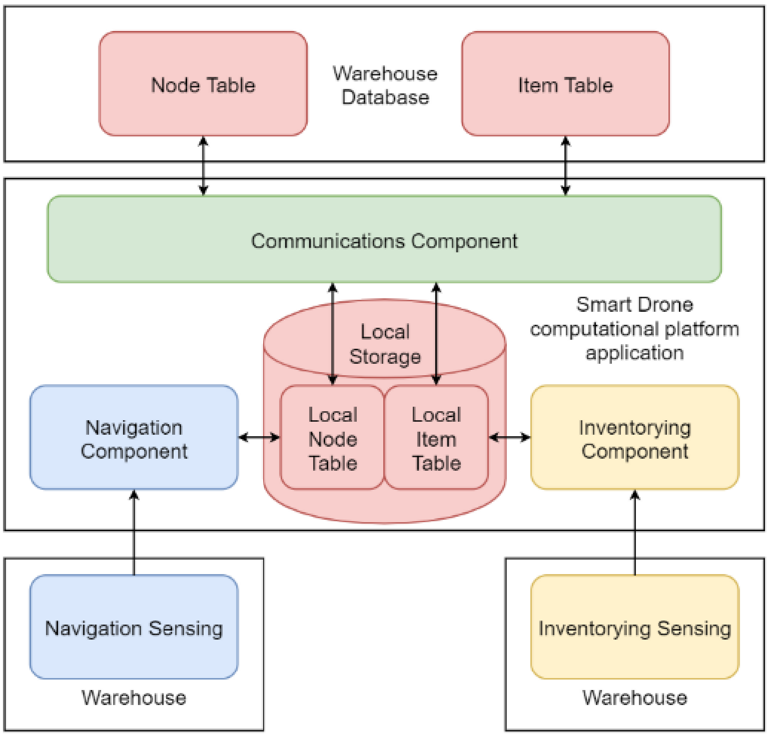


Figure 4. 6 System components (adapted from [89])

Inventorying Component

As previously said, the main objective of the inventorying component is to process the information contained in the tags attached to the items to be inventoried. The tag reader to be installed in the drone is a RFID sensor system and the warehouse sensors to be used are the passive RFID tags, for reasons already discussed on Section 3.3.1 of this dissertation. Preferably the RFID sensor system should be EPC Class 1 Gen 2. The system allows both Signalling and Bulk Reading RFID query methods, in the 860 Mhz to 960 Mhz range (UHF). It is an established standard with a range upwards of 2 metres. It supports several readers and the Cycle Redundancy Check (CRC-5-EPC) error detection method is implemented [89]. As for the RF-ID tags, these needs be affordable in bulk and ideally reprogrammable, and it should be easy to put on the items, as previously referred. The tags should contain the follow configuration:

- **Electronic Product Code** (EPC) or the tag's unique identifier.
- **Numeric** indicator for the item's **quantity** in the storage unit.
- **Item Coordinates** for the item's planned storage position.

This configuration will help us not only count the product but identified misplaced items.

The software architecture of the inventory component should be consulted in the Attachment 3.

Navigation Component

The basic function of this component is to allow the drone to fly autonomously throughout the warehouse according to a virtual map. It is intendent to use RFID tags (node tags) to compute the drone's position. The RFID tags are different from the ones used for the inventorying component, in the sense that they don't have information of items. They just serve the only propose of feeding coordinates to the navigation component. This component will create a virtual map that will guide the drone based on the Dijkstra's algorithm for the shortest path [89].

The navigation component is the most complex component in the system. Various approaches should be evaluated. Consult Attachment 4 for the Received Signal Strength Indication (RSSI) Triangulation approach to the software architecture of the navigation component, Attachment 5 for the top-down view of the drone navigation solution in an example configuration and finally Attachment 6 for the Course Correction approach to the software architecture of the navigation component.

In addition, the node tags can have different uses according with if we choose to implement the RSSI Triangulation approach or the Course Correction approach. Portela et al. identifies that for the RSSI Triangulation approach, "these tags should be divided into two sets to serve as markers and boundaries. The markers should be programmed with a point of the virtual coordinates map. These will act as anchors for the drone to compute its distance to, through RSSI. The boundaries can be placed onto surfaces where the drone should not go near, such as shelves. The drone should stop moving in the direction of the boundaries when a certain RSSI threshold is reached." Also, Portela et al. cites that for the course correction approach "a single set of RFID tags will serve as node tags and complement a brightly coloured visual marker. The node tags should be placed on the wall at the ends of an aisle. The node tags each contain a set of two values for the horizontal coordinates where they are to be placed."

Communications Component

The communications component communicates directly with the local storage and with the Warehouse database. These communications aim to update the warehouse database based on the information stored in the local storage. These updates happen periodically and whenever a Wi-Fi connection is available, through a reliable transport layer protocol such as TCP. Furthermore this component should be able to audit the information contained in the local storage, issuing discrepancies reports when the information of the local database and the warehouse database don't match.

According to Figure 4.5, once the drone is attached to the SBC and the SBC is connected via USB to the RFID reader and via Wi-Fi to the warehouse network, the component must be able to perform tasks related to the Inventorying Component and the Navigation Component**.**

Regarding the Inventorying Component the system should perform the following tasks:

- **Retrieve information** of the items, by triggering the RFID reader query the identification tags.
- **Update** the warehouse database whenever a Wi-Fi connection is available.
- Issue **discrepancies reports** identifying misplaced items by comparing the tag responses with the drone's position at moment of scanning.

As for the navigation component, the system should be able to communicate the following information:

- Drone's **position** by evaluating its surroundings.

- **Drive** through a warehouse with varying layouts and dimensions.
- Identify **path issues** and retrieve when something is not working accordingly.

The software architecture of the communications component should be consulted in in Attachments 5.

Local Database

The information contained in the Local Item table and the Local Node Item constitute the Local Database, as seen in Figure 4.6.

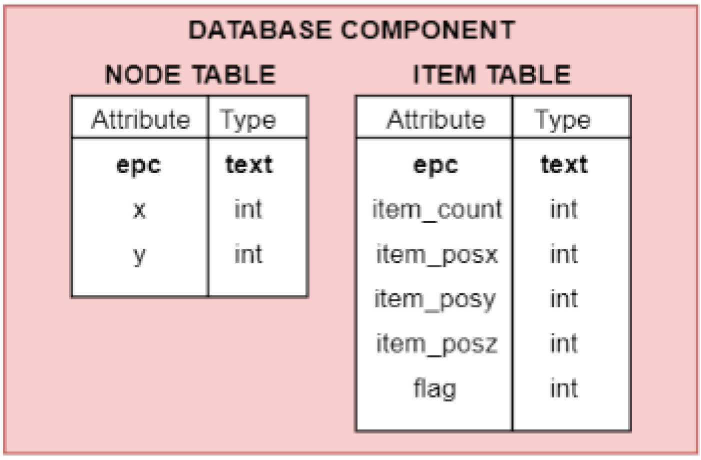
The **Item tag** information is stored in the Local Database in the following format:

- **Electronic Product Code** (EPC) or the tag's unique identifier.
- Numeric indicator for the **item's quantity** in the storage unit.
- **Item Coordinates** for the item's planned storage position in x-y-z axis position. The node tag position (x,y) closest to the item and the shelf level (z) that the item is on.
- **Flag**. A tag is marked as a misplaced item if its flag value is 1. Otherwise is 0.

As for the **node tag** information, its stored in the Local Database in the following format:

- **Electronic Product Code** (EPC) or the tag's unique identifier.
- The **node tag position** in x-y axis position.

Figure 4.7 exemplifies how the Local Storage stores the information of item and node tags.



DATABASE COMPONENT

NODE TABLE

Attribute	Type
epc	**text**
x	int
y	int

ITEM TABLE

Attribute	Type
epc	**text**
item_count	int
item_posx	int
item_posy	int
item_posz	int
flag	int

Figure 4. 7 Local Database (adapted from [89])

Finally, with the full understanding of how the subsystems of the UAV based system prototype work, we are in position to describe the cycle counting procedure using this system.

First off, the item and node tags should be deployed throughout the warehouse. This system relies on both to do the cycle counting. Once the tags are deployed, the system illustrate in Figure 4.5 can be launched through the application by an operator. The Navigation Component takes over the system. The UAV based system proceeds to hover and begins to autonomously move according to a pre-calculated route through the shelves. This route is optimized based on the Dijkstra's algorithm for the shortest path, in order to cover the storage area with the least amount of movement possible. The drone moves from node tag to node tag. These tags are deployed in strategic intermediate points in the aisles floor of the warehouse. The drone only moves to the next shelf level once the entire previous shelf level has been scanned using the RFID tag reader. The drone continues this process, using its navigation component, until all shelf levels have been scanned. During this movement, the inventorying component is processing the data from the RFID tag reader and storing in the Local Database. If a connection to the warehouse database endpoint is available, it will attempt (through its communication system) to update the warehouse database through Wi-Fi. In parallel the information inside the node tags are being transmitted to the warehouse database as well. If the drone happens to stray from its original course, it corrects itself once it reaches a checkpoint in its path. If everything goes accordingly with the route calculated in the beginning, and the system scan every item, the drone returns to its starting position. In the meanwhile, the communication component is updating the warehouse database. If any of the item is flagged, with “1”, it issues a discrepancy report because that item is misplaced. Nevertheless, when the drone returns to the starting point, the warehouse database should be fully updated with near real time information. The cycle counting procedure is finished.

In Figure 4.8, a three-dimensional system overview done by student of METI is presented. This 3-D representation aims to represent the UAV based system doing the cycle counting procedure inside a warehouse.

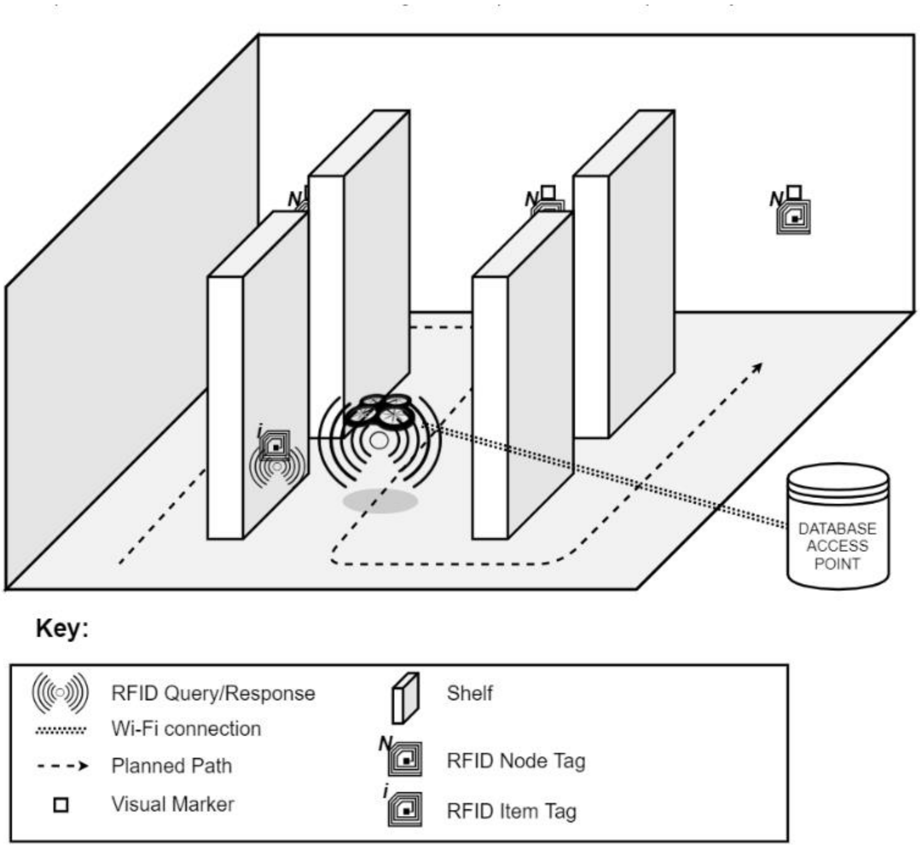


Figure 4. 8 Three-dimensional system overview. Cycle counting using drones (adapted from [89])

The divergences between current cycle counting procedures depicted on section 4.2.1, and future processes presented above, serve as a basis for the construction of the business case. The identified opportunities for improvements identified will be detailed in the next section of the methodology.

4.3 Opportunities for improvement

The objective of this section is to characterize, organize and categorize the opportunities for improvements for the cycle counting activity using drones in the warehouse.

In section 3.4.2 of this dissertation a lot of explanatory arguments were given in favour of the adoption of drones in warehouse operations. It was said that, in short, when used for cycle counting, drones can ensure inventory accuracy, reduce operational costs, and improve employee safety in warehouses. Despite the fact that this is plausible, not all of these benefits will be a reality for every warehouse. Although there is no literature on the benefits that are expected to arise with the investment on drones to do the cycle counting activity, we can presume this benefits by looking in the literature for similar business cases' related to warehouse technologies such as the WMS, and adapt that to drones and cycle counting. This may be a clever approach because drones can be seen as an augmenting technology. By augmenting the existing technologies such as a WMS, drones can help improve the RoI on existing infrastructures.

The knowledge acquired in the previous sections 4.2.1 and 4.2.2, support the presumed expected benefits the drones will bring to the current process of cycle counting. This is not satisfactory however, because we need to identify which changes the implementation of drones will cause in **metric values** to construct a **business case**.

This section includes all the benefits that can be presumed that the implementation of drones can bring. Each benefit is explained, in order to allow the readers of this work to reproduce the methodology and analyse which benefits coincide with its case. These benefits have been adapted from business cases on the implementation of a warehouse management system [90] and have been divided into five categories represented in **Figure 4.9.**

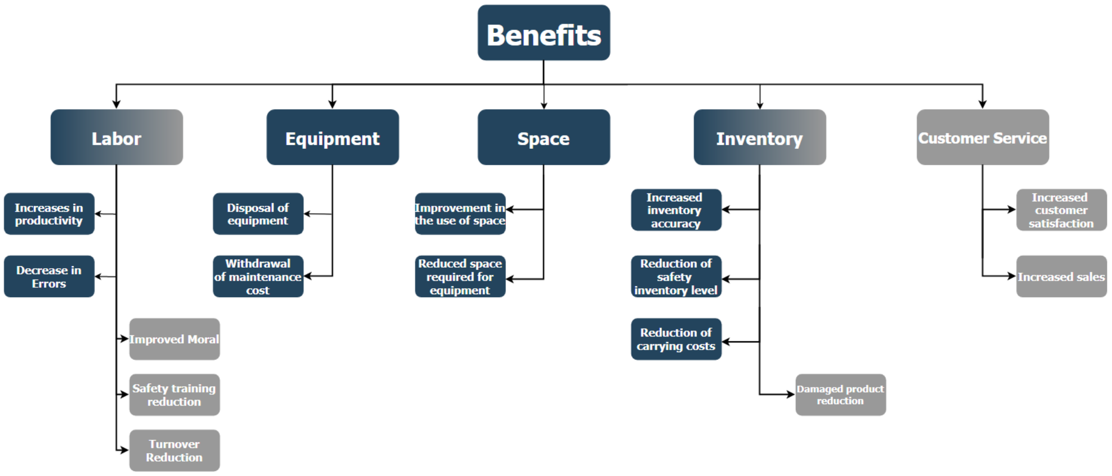


Figure 4. 9 Benefits Resulting from the automation of the cycle counting activity using drones (adapted from [90])

The above benefits are divided into **qualitative** and **quantitative** benefits (or **savings**). The **qualitative** benefits are identified with **gray tint** and the **quantitative** benefits are identified with the **blue tint**. The last should be evaluate in **magnitude**. This can be done by looking at the **metrics** used to assess the **performance** of the **cycle counting** and comparing that with the **opportunity** for **improvement**. It is necessary to establish the changes that drones will bring to cycle counting (already identified in section 4.2.2) and what **values** are expected that these **performance metrics** will have. After knowing the **current** and **expected value** of the **performance metrics**, it is then possible to give a **magnitude** to the expected **savings**. This distinction will influence the way each benefit is included in the business case. The qualitative benefits being included in the **narrative** form and quantitative benefits being included together with the **costs** constituting the economic justification of the project [90]. Additionally to dividing the above benefits into qualitative and quantitative, benefits can also be classified as **recurring** or as **punctual**. This difference is important to compute the savings across the life of the system.

The prototype to be developed between the author and another student from the MSc in Telecommunications and Informatics, is a proof of concept. That said, not all the expected benefits can be achieve by the proof of concept prototype. Nevertheless, in this section we detail all the expected benefits for use on future business cases.

1. Benefits Related to Labor

The benefits related to labour represent the largest share of the total benefits obtained with the automation of cycle counting using drones.

Labor can be classified into direct, indirect, and administrative. The direct labor force consists of the workers who are doing the cycle count, known as “cycle counters”. Usually these are the most experienced employees. These employees already know the products very well, thus they are going to be accurate and accomplish this task faster. They take care of the third step of the cycle counting procedure. Indirect labor is made up of the workers responsible for the supervision of the cycle count, inventory control and the training of the new “cycle counters” when they are new to the procedure. These workers usually complete the first two steps of the cycle counting procedure: complete data entry on all inventory transactions, so the inventory database is fully updated and print the report and assign it to the direct labor. Lastly, the administrative workforce is made up of workers responsible for the last three activities of the cycle count. They will investigate if there are any differences between the records on the WMS and the results obtained in the cycle count. They will modify the process to alter the error and will adjust the inventory record database to remove the error found by the cycle counter.

The proposed UAV system is designed to not be dependent on human labor to operate, being as autonomous as possible. Thus, the system will aim to eliminate the need for people to perform this repetitive and dull activity. With regard to direct labor and indirect labor, their work will be completely replaced. This replacement will generate quantitative benefits and qualitative benefits, one being the shift from “cycle counters” to strategic decision-makers and problem solvers. This adoption will also eliminate the errors related to the human error.

Additionally, this replacement will increase worker safety, saving a lot of money in the meanwhile. Safety incidents involve forklifts, loading docks, goods conveyors, hazardous materials storage, and manual lifting account for thousands of human injuries and millions of lost worker-days each year. Insurance premiums, Occupational Safety and Health Administration (OSHA) fines, healthcare/death compensation settlements, safety training & audits all put a significant dent in profit margins for many warehouses [57].

The increase in the productivity of the administrative workforce is due to the access to better information as better information means less time spent confirming data in the system. In addition, the system is designed to issued flags for misplaced items. The set of these items constitutes the discrepancy report. These discrepancies reports otherwise would be issue by the administrative workforce. Nevertheless they will still have to modify the process to alter the error and will adjust the inventory record database to remove the error found by the UAV system.

Additionally, as previously said, the cycle count is a repetitive and dull task. Thus, the automation of cycle counting using drones will lead to an improvement in morale and job satisfaction and at the same time reduce the turnover of the workforce.

We can also think about the indirect benefits that a fully near real time information updated warehouse database will bring to other activities such as picking and replenishment. By ensuring the information on the WMS, about the availability of inventory before indicating the location where the worker must pick up the products, the UAV system augments the WMS potential of reducing time spend traveling in the warehouse and the time spend waiting for a product to be replenished. Similar to the benefits to the cycle counting, by reducing the time spend traveling around the warehouse for picking and replenishment, the UAV system leads to a reduction in the distance travelled and thus leads to a reduction in accidents.

2. Equipment Related Benefits

As previously mention with the automation of cycle counting using drones, the system will aim to eliminate the need for people to perform the cycle counting procedure. This will result in a reduction in the number of workers. This reduction will result in a reduction in the associated equipment as well. If the equipment is rented, this reduction leads to an elimination of the rental fees paid. This will release funds to be invested in other projects. Otherwise, if the equipment is owned by the company, the benefit results from the sale of this equipment generate a punctual positive cash flow. The benefits from the elimination of the rental fees or from the sale will also result in less maintenance costs [90].

3. Space Related Benefits

In similar fashion to the equipment related benefits, if the automation of cycle counting using drones leads to a reduction in equipment, then the space needed to store and repair it will also decrease.

Additionally, the proposed UAV system provides near real time inventory levels. This near real time information allows a reduction in the levels of the safety inventory level. Thus the UAV augment the information of the WMS and allows a better consolidation of the inventory and thus management of the available space, improving the use of the existing storage space. If the warehouse is owned by the company that will implement the drone in the cycle count, the creation of empty space resulting from a better use of space or from the reduction of space needed to store the equipment, produces benefits in cases where the amount of empty space is sufficient to be used in other activities such as renting spaces for other companies for example. Otherwise, if the warehouse is rented per occupied square meters, the creation of empty spaces will reduce the cost of renting it [90].

4. Inventory Related Benefits

The cycle counting procedure is designed to improve inventory accuracy. The proposed UAV system aims to deliver a 100% inventory level accuracy in near real-time. Often, the lack of confidence about the inventory levels leads to an increase of the safety inventory levels. The 100% accuracy inventory level in near real time gain from the automation of the cycle count using drones, leads to a increased confidence in the information about the inventory levels kept in the warehouse, which allows to reduce the safety levels without affecting the level of customer service. This reduction leads to a reduction of the carrying costs associated with inventory, which comprises between 25% and 35% of the total value of the inventory. These carrying costs are divided into four: cost of capital (investment on inventory), cost of services (includes costs with insurance and taxes), cost of space (already discussed previously) and costs associated with inventory managements risks (includes costs with damaged or obsolete inventory). Additionally, Barnes et al., says that a better use of space and a decrease in the level of inventory reduces the need to use corridors and other “non-locations” as a storage location, which can lead to a reduction in the number of damaged goods. At the same time, products are more prone to damage if a human is doing the cycle count.

5. Customer Service-Related Benefits

The UAV system adoption will augment the WMS capacities. This will have massive benefits related to the customer service. The improve of accuracy on inventory levels at the warehouse, augment the ability of the WMS to minimize the time it takes between placing and receiving an order, because there is no discrepancies between the quantity on the shelf and the on-hand quantity in the WMS. This decrease can lead to an extension of the deadline that the company offers for placing order, which can mean a competitive advantage and consequent increase in sales. These benefits are mainly qualitative because it is hard to how much business will be generated from this competitive advantage.

Although all benefits are included in the business case (**qualitative** in **narrative** form and **quantitative** benefits in the **economic justification** of the project), those that are not supported by solid evidence can be bad perceived by the management team of the company. Therefore the team responsible for the construction of the business case must do its best to quantify all improvements. This is extremely important in investments like this, which little is known in the literature about its benefits.

4.4 Savings Estimate

In this section of the methodology, the methods used to estimate the benefits are detailed. As previously said, there must be an effort to quantify all improvements. The only benefits that can be quantify are the ones in blue tint in Figure 4.9. In the best interest of the reader, it is important to mention that the methods used to estimate the quantitative benefits were based on business cases on the implementation of a warehouse management system [90] and by looking at the metrics used to assess the performance of the cycle counting.

The prototype to be developed between the author and another student from the MSc in Telecommunications and Informatics, is a proof of concept. That said, not all the expected benefits can be achieve by the proof of concept prototype. Nevertheless, in this section we detail all the savings expected for use on future business cases.

1. Benefits Related to Labor

Increases in productivity

As stated in section 4.3 the autonomous UAV system is designed to not be dependent on human labor to operate. The system will perform the cycle counting without human intervention, so the direct and indirect labor will be completely replaced. As in all autonomous systems adoptions, the increase in worker productivity is mainly due to a reduction in the total number of hours spent doing cycle counting previous to the implementation of the technology. It important to note that there is no downside of this reduction because the company will still be able to support the same volume of business with fewer workers (reduced labor). In the case that this implementation increase the volume of the business, the company could simply shift the work of the “cycle counter” that was replaced, to address this business rise thus preventing the need to hire more workers (eliminating the need for hire more labor) [91].

When the UAV system makes it possible to eliminate the need for people to perform cycle counting, the reduction in the number of hours worked can be translated into the number of FTEs[11], that is, the number of workers who can be reduce or who are available to support an increase in the volume of business. To calculate the savings, first we need to quantify the time these “cycle counters” spend to perform the cycle count and divide that by the number of hours worked by a full-time worker (FTE) [91]:

$$Labor\ (FTEs) = \frac{Total\ hours\ Saved\ (Hours)}{Total\ hours\ per\ worker\ (\frac{hours}{FTE})} \tag{4}$$

Thus, the savings resulting from the reduction in labor can be calculated through:

$$Saving\ (€) = Labor\ (FTEs) \times Cost\ per\ worker\ (\frac{€}{FTE}) \tag{5}$$

All the data must be in temporal agreement.

Decrease in Errors

If the proposed UAV system deliver a 100% accuracy on scans, this system can eliminate the errors associated with manually entering information into the system during the cycle counting. To quantify the savings resulting from this decrease, it is necessary to understand how many manual information insertions are currently made in the cycle counting activity. We can draw a parallel for errors related to entering information during the cycle count. For every 300 times a worker clicks on a keyboard to enter information, an error is produced [90]. Following the same logic, for the same of times a “cycle counting” clicks on a keyboard to enter information, an error is produced. Thus, the number of errors that will be eliminated is obtained by multiplying the number of manual insertions by the number of errors per insertion (1/300). The savings can be computed as follows:

$$Savings\ (€) = Number\ of\ erros\ elminated\ (\#) \times Cost\ of\ correcting\ each\ error\ (\frac{€}{\#}) \tag{6}$$

2. Equipment Related Benefits

Disposal of equipment

The savings related to the disposal of equipment, are related to the reduction of the number of workers that will result from the implementation of drones in the cycle counting activity. These workers use a variety of equipment to perform the cycle counting (for example, forklifts to achieve the highest level on the shelfs). On the other hand, in the case that this implementation increase the volume of the business, this results in a cancellation of purchasing or renting more equipment. The number of equipment that is reduced or avoided to be purchased/rented can be computed as follows:

$$Disposal\ of\ equipment\ (\#) = Reduction\ of\ Labor\ (FTE) \times Equipment\ by\ FTE\ (\frac{\#}{FTE}) \tag{7}$$

---

[1] FTE (*Full Time Equivalent)* refers to the ratio between an employee’s scheduled hours and the employer’s hours for a full-time workweek in the same time interval. This ratio then indicates the number of equivalent workers working full-time.

Barnes et al., cites that the value computed in expression (7) varies between 5 and 25% of the total value of the equipment. That same estimative can be applied to our case. In that case, the savings that result from the sale or the elimination of rental fees paid for the eliminated equipment, are given by:

$$\begin{gathered} Savings\ (€) = Disposal\ of\ equipment\ (\#) \times \\ Rental\ cost\ or\ Resale\ Price\ per\ Equipment\ (\tfrac{€}{\#}) \end{gathered} \tag{8}$$

Withdrawal of maintenance cost

By reducing or avoiding purchasing/rental more equipment, the company also withdraws the maintenance costs spent on them. The maintenance costs divide into two: parts used in the maintenance of the equipment and the worker doing the maintenance. The savings can be computed as follows:

$$Savings\ (€) = Disposal\ of\ equipment\ (\#) \times Costs\ of\ maintenance\ per\ Equipment\ (\tfrac{€}{\#}) \tag{9}$$

3. Space Related Benefits

Improvement in the use of space

It is difficult to quantify the improvement that the UAV system will generate in the use of space. This difficulty is largely because the UAV augment the information of the WMS, but it is the WMS that allows for a better consolidation of the inventory and thus management of the available space, improving the use of the existing storage space. In other words, by doing the cycle counting faster the UAV system ensures that there is no discrepancies between the quantity on the shelf and the on-hand quantity in the WMS. In doing that, the WMS could achieve its full potential and consolidate the inventory in a better way. According to Barnes [90], the improvement in the use of the existing space done by the WMS, varies between 5% and 30% of the total space. Ideally this benefit should be quantified comparing the improvement with just the WMS and then the WMS plus UAV system to see the impact of having near real time inventory level information has on the improvement in the use of space. Nevertheless, if the warehouse is rented based on the occupied square meters, the creation of empty spaces allow to reduce the costs of renting it. If, in the other hand, the warehouse is owned by the company, the creation of empty spaces produces savings when the amount of empty space is sufficient to avoid the construction of new storage areas or when the empty space can be rented [90]. The savings can be computed as follows:

$$Savings = Stored\ space\ (m^2) \times \%\ Improved\ Use\ \times rental\ per\ m^2\ (\frac{€}{m^2}) \tag{10}$$

In expression (10) the rental per m^2 can refer to the rental price that the company pays or the amount that the company will charge [91].

Reduced space required for equipment

The disposal of equipment will mean that there more space where that equipment was sitting. The reduced space required for equipment is pretty straightforward and can be computed as follow:

$$\begin{gathered} Savings\ (€) = Disposal\ of\ equipment\ (\#) \times Space\ by\ equipment\ \left(\frac{m^2}{\#}\right) \\ \times\ rental\ per\ m^2\ (\frac{€}{m^2}) \end{gathered} \tag{11}$$

4. Inventory Related Benefits

Increased inventory accuracy

In the literature [91], the expected inventory accuracy expected after the implementation of a WMS is at least of 99%. Similarly to the discussion above in the improvement in the use of space section, the UAV system ensures that there is no discrepancies between the quantity on the shelf and the on-hand quantity in the WMS. If after the implementation of the WMS the inventory accuracy expected was of at least 99%, if the UAV system could be faster and read the items tags in near real time with 100% accuracy, the inventory levels of the WMS would match the reality. The increase in inventory accuracy can thus be calculated by subtracting the current inventory accuracy of the warehouse from the expected value after the adoption of drones (100%). This accuracy will depend on the performance evaluation of the UAV system.

Reduction of safety inventory level

It is expected that the combination between WMS and the UAV system will lead to an increased confidence in the information about inventory levels in the warehouse which allows to reduce its level. The WMs alone can reduce the inventory level between 5% and 20% of the total inventory [91]. Ideally this benefit should be quantified comparing the improvement with just the WMS and then the WMS plus UAV system to see the impact of having near real time inventory level information has on the reduction of safety inventory levels. Nevertheless, the savings are calculated by multiplying the inventory value by the expected increase of the inventory accuracy as follow:

$$Savings = Inventory\ Value\ (€) \times \%\ Increased\ accuracy \qquad (12)$$

Reduction of carrying costs

By causal relationship, the reduction of safety inventory level will reduce the carrying costs of having these inventory stored. These costs are very relevant and comprise between 25% to 35% of the total value of the inventory [90]. The savings resulting from this reduction are calculated as follows:

$$Savings = Inventory\ Value\ (€) \times \%\ Increased\ accuracy\ \times \%\ Carrying\ Costs \qquad (13)$$

4.5 Costs Estimate

The construction of the business case is incomplete without the costs estimate. It is necessary to quantify the costs associated with the UAV system. These costs will be included in the economic justification as negative cash flows. To estimate these costs we can rely on Figure 4.5 for hardware costs and Figure 4.6 for software costs. Table 4.6 summarizes the cost structure.

Table 4. 6 Cost Estimate of the proposed UAV RFID System

	Cost (€)
Hardware	
UAV	
Tag Reader	
SBC	
Identification tags	
Software	
Communications Component	
Navigation Component	
Inventorying Component	
Local Storage	

4.6 Economic Justification

After achieving the savings and costs that will arise after the implementation of drones in the cycle counting activity, it is necessary to compare these cash flows in order to understand whether the project will be economically advantageous for the company. In typical projects, the main criteria for accepting or rejecting a project are the Net Present Value (NPV), Payback Period, Internal Rate of Return (IRR) or Return on Investment (ROI). The first two are the most used. In the case of these tools it is necessary to determine the period of time over which savings and costs will be calculated. In public investment, a longer project time horizon is considered (~ 30 years), because there funding came from taxes, fees or bonds and they have to leverage different multiple selection criteria. Additionally, normally this projects have a large size of investment, In the other end, private investment as a small to medium investment depending on the size of the company, have a shorter project life (2 to 25 years maximum), their annual Cash Flow is profit-driven and their primary selection criteria is ROI. The most frequently used value for this time horizon is private projects is 5 years.

As previously said, the prototype to be developed between the author and another student from the MSc in Telecommunications and Informatics, is a **proof of concept**. The type of economic justification presented above, is **not suitable** for a proof of concept system. The major realization of a certain proof of concept is to demonstrate **its feasibility**, not their **economic viability**. In other words, the proposed UAV system is a demonstration in principle that the system has practical potential for the **cycle counting activity**. With this, we are not saying that an economic justification should not be done. On the contrary, we are saying that for such a preliminary system, if we choose to apply the NPV, Payback Rule, IRR or ROI, this approach **lacks rigor** and approaches that lack rigor are received **skeptically** by top management.

A better approach to convince the top management and to avoid this lack of rigor, is to reduce the complexity of the economic justification. If there is no proper literature on the benefits that drones and we are not sure about the KPIs that the proposed UAV system will present while doing the cycle counting, the better solution is to do an **Economic Justification** related to a **Use Case** proof of concept. In short, if the top management does not trust that the proposed system is actually going to deliver the benefits that were stated in the business case, it is useful to do an Economic Justification on the use case to figure out if the ROI would be good.

In this case, it makes sense to first understand what **unit economics** are and why they are relevant for the economic justification in this case. Units economics generally comprise the vision where instead of looking at a **business investment** form a revenue perspective or overall profitability perspective, we analyze the new processes after the investment, and see how these new processes compare to the old processes in terms of **unit economics.** This approach removes the importance to established time horizons of 5 years, because it assumes that there is too much uncertainty about the project to estimate good values of Cashflow along that years. Instead it looks for **how much** is **gained each time** the **new** system performs the **work** that **otherwise** was performed by the **old** system. This is a particular good framework to justify economically the implementation of drones in the cycle counting activity because this is an activity that is regular of business' processes. In the case that the proposed system (new system) performs better than workers (old system), this is a very recurrent benefit and we could see its impact by analysing the **unit economics** of this process.

Nevertheless, if one chooses to use the NPV method or the Payback Period, there are three main aspects to keep in mind. The first is related to when savings are considered during the 5 years normally considered. The quantitative benefits identified are not immediately felt by the companies, because in months right after the beginning of the use of the proposed system, workers are still getting used to function with it. For this reason, some companies choose in the business case to consider the value of savings in the first year as being half the value of savings in the remaining years considered. The second aspect is related to the number of times each savings is considered. These can be recurrent, or they can occur only once, and it is important to classify each quantitative benefit according to this concept. Of the savings identified, those that are generally considered to occur once are the one computed using the expression (8) and (12). The third aspect to consider is how recurrent savings vary over the 5 years normally considered. To calculate these variations, it is necessary to consider data such as the average increase in the cost of workers, annual business growth, and others [90].

Yet, whichever method is chosen, to strengthen the credibility of the business case a sensitivity analysis should be performed.

4.7 Chapter conclusions

Usually the development of the business case, for an adoption of a technology, implies a great knowledge of how the technology works and how it will change the operations of the company where the technology will be implemented. In the instance of this dissertation, the technology itself and the use case where the technology will be implemented until this chapter, were unknown.

Firstly, a concrete analysis was conducted to find the highest use case potential for the use of drones in warehouses. The North Star Metric Framework was used to conduct this analysis. This framework help to define a metric or leading indicator, that defines the relationship between the customer problems and the long-term business results. In the first layer, to decide between Intra-logistics, Inventory Management and Inspection Surveillance, the north star was the state of drone technology. This theme was extensively discussed at section 3.2. This preview discussion helped to choose the Inventory Management field as the most promising field. The Inventory Management field have numerous and different tasks. For this layer the North Star was the Return on Investment with two input metrics, ease of drone automation adoption and crave for cost effective operations. Each task was analyzed according to these metrics and the cycle counting use case showed the highest potential use case for the use of drone in warehouses. Despite that, the tasks are not mutually exclusive.

Secondly, an extensive description of the processes that occur today in the cycle count was given in order to identify the current limitations of these processes and thus conclude about the expected improvements. The three main limitations of this process fall into three categories: very intensive-dangerous labor activity, time to perform the activity and lack of accuracy on discrepancies reports. With the information gathered in this step, we were able to present the proposed design of the UAV based system prototype aimed to perform cycle counting. This system has four main components: Inventorying component, navigation component, communications component, and a local database. The prototype to be developed between the author and another student from the MSc in Telecommunications and Informatics, is a proof of concept**.** The proposed communications architecture consists of a UAV, a SBC, a Tag Reader, Identification Tags, and a USB. The cycle counting procedure using this system was presented with the help of a three-dimensional system overview.

Finally, after the use case was identified and the prototype presented, it was possible to identify the various benefits in section 4.3, quantify the savings in section 4.4 and predict the costs in section 4.5.

5. Data treatment | UAV implementation

This chapter explains the main data obtain by the student of METI. The data obtain via experiments and tests is latter used in the results section to build the business case. All the data presented in this chapter were obtained exposing the prototype to defined scenarios build in partnership with the the author and another student from METI. This system was used to test different scenarios. An overview of the environment where tests were done is presented. Additionally, all simplification strategies used, and necessary assumptions are also provided.

5.1 Implemented Architecture

Figure 5.1 portray the **actual implemented communications architecture** by the student of METI . The actual implementation is faithful to the proposed architecture (Figure 4.5). In order to perform the cycle counting, an RFID Reader (**WRD-130-U1 UHF RFID card reader**) is carried by a **DJI Ryze Tello EDU** drone. Regarding the used RFID tags, they are **ALN-9662, Higgs-3," Short" Inlay type tags**, that can be read with the RFID card reader. The RFID card reader is connected through an USB Wi-Fi Adapter (**TP-Link TL-WN321G 54 Mbps Wireless USB Adapter**) to the SBC (**Raspberry Pi Zero**). The item tag information contained in the ALN-9662, Higgs-3," Short" Inlay type tag, is first storage in the local storage (Figure 3.10) of the SBC and then sent through Wi-Fi to the warehouse database, which, for the experiments performed in this dissertation, was run in the **laptop** of the METI. A brief definition of each component implemented by the student of METI is given to give context to the reader.

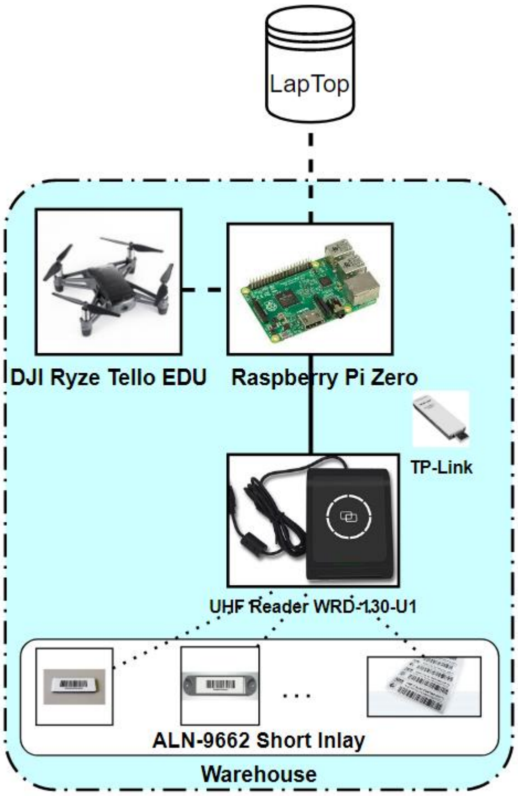


Figure 5. 1 Implemented communications architecture

5.1.1 UAV

As previously said, the prototype to be developed between the author and another student from the MSc in Telecommunications and Informatics, is a proof of concept. The implementation of the UAV was done based on the joint definition of specifications and requirements.

As discussed in section 3.1, UAVs vary widely in size, components, sensors and configuration. In the design of the proposed UAV, the main objective was to develop a cost-effective prototype capable of doing the cycle counting. **Figure 5.1** portray the selected UAV, while **Table 5.1** shows a summary of their characteristics. This drone is a **Quadcopter**. This type of multi-rotor drone offer a good trade-off between **cost**, **payload capacity** and **reliability**. A **Quadcopter** offers a more efficient flight experience and it is more stable than an octocopter. On the other hand, more rotors increase the reliability but would also increase the cost and its total weight thus not justifying choosing the octocopter. Regarding the trade-off between cost and payload capacity, the ideal situation would be that the quadcopter had managed to carry a load of around 300*g*, to be able to carry the SBC and the tag reader. Yet, neither commercial solution in the market offered that payload capacity. Thus, the selection of the drone fell on the **DJI Ryze Tello EDU**. This drone has a good price range, have VTOL and hover flight capacity, can operate in the limited aisles with safety and are easy to implement. Additionally, this drone is programmable which is far more important that the payload capacity. It is expected that in the future, these types of drones will maintain its programmable capabilities and will become capable of having a higher payload capacity to carry the SBC and the tag reader. It is important to continue to extend their battery life as well. Additionally, the **DJI Ryze Tello EDU** has its own proprietary **Software Development Kit** (SDK) which helps the implementation of the software. The information gathered in this section is found on Tello's specification documents, namely the Tello User Manual v1.2[2]

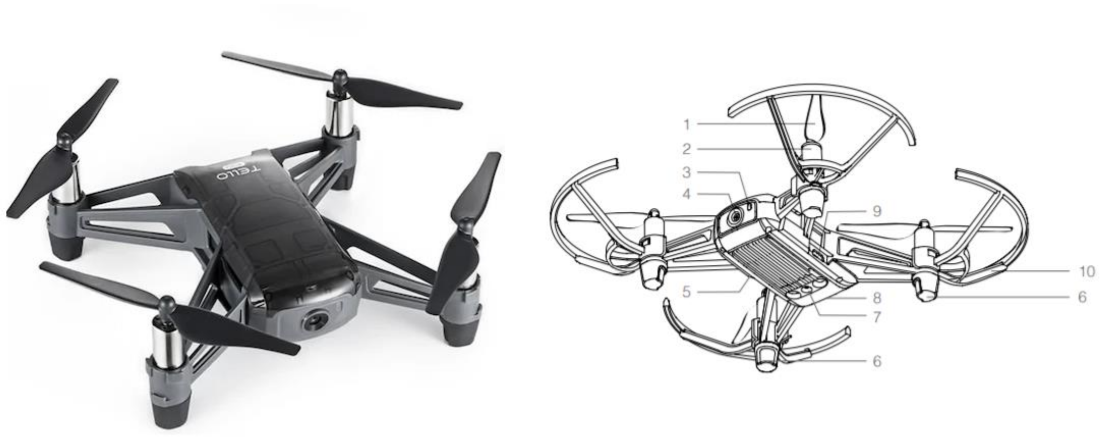


Figure 5. 2 DJI Ryze Tello EDU (adapted from the Tello User Manual V1.2[2])

The Aircraft Diagram caption is as follow:

1. Propellers
2. Motors
3. Aircraft Status Indicator
4. Camera
5. Power Button
6. Antennas
7. Vision Positioning System
8. Flight Battery
9. Micro USB Port
10. Propeller Guards

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[2] User Manual: https://dl-cdn.ryzerobotics.com/downloads/Tello/20180404/Tello_User_Manual_V1.2_EN.pdf

Table 5. 1 Specifications of the UAV (adapted from the Tello User Manual V1.22)

DJI Ryze Tello Edu (Model: TLW004)	
Weight	87g
Max Speed	8 m/s or 28.8 km/h
Max Flight Time	13 minutes (0 wind at consistent 15 km/h)
Operating Temperature Range	0° to 40°C
Operating Frequency Range	2.4 to 2.4835 GHz
Transmitter (EIRP)	20 dBm (FCC) *America* 19 dBm (CE) *Europe* 19 dBm (SRRC) *China*
Camera	
Max Image Size	2592x1936
Video Recording Modes	HD: 1280x720 30p
Video Format	MP4
Flight Battery	
Capacity	1100 mAh
Voltage	3.8 V
Battery Type	LiPo
Energy	4.18 Wh
Net Weight	25 ± 2g
Charging Temperature Range	5° to 45°C
Max Charging Power	10 W

To perform the cycle counting activity the DJI Ryze Tello EDU has to be able move in all directions, forward, backward, left and right, along with being able to gain and lose altitude and rotating in order to perform turns once the end of the aisle is reached. The Vision Positioning System (VPS) of this drone helps the drone to hover in place more precisely and fly indoors in windless conditions. The main components of the Vision Positioning System are a **3D infrared emitter/receiver pair** and a small **camera** located on the underside of the drone. In the more screen the user can calibrate the **Inertial Measurement Unit** (IMU). The IMU keeps track of its pitch, roll and yam. The VPS is activated automatically when is UAV is turned on. Some limitations were identified in the VPS and will be discussed in the chapter 6.

5.1.2 RFID Reader

The conclusion reached in the literature review was that, based on the analysis of the Attachment 1, that High frequency RFIDs when compared with Low frequency RFIDs seem a better option. Both technologies require no power, both have non-line-of-sight propagation (NLOS) and no need for battery and can be integrated with smart devices of Industry 4.0 but HF RFID allow for larger reading ranges. This is specific important if we think on security purposes. In LF RFID the drone would have to be as close as 10 cm to read the label which can be very dangerous. In accordance with this analysis, the RFID Reader chosen was a **WRD-130-U1 UHF RFID card reader.** This RFID Reader was chosen because is compatible with the EPC class 1 Gen 2 type RFID Tags, has a desktop UHF reader/writer, support USB and has a reading distance up to 15cm. **Table 5.2** shows a summary of its characteristics.

Table 5. 2 UHF Reader WRD-130-U1 specifications

UHF Reader WRD-130-U1	
Frequency	865-868MHz / 902-928MHz
Protocols	EPCC1G2 ISO 18000-6C
Interface	USB-Keyboard emulator/HID/USB CDC
Supply voltage	USBPort (3-7 VDC)
RF Power Output	0~18 dBm, adjustable
Operation range	10 to 100cm (depend on tag)
Operation temperature	0° to 50°C
Dimension	120x85x25mm
Weight	~141g

Note: When the RFID Reader scans the tag, the led become green and it issues a sound.

The weight is highlighted in red because this a problem. The RFID Reader is itself heavier that the drone. This implies that the drone is not capable to carry this RFID Reader. This is a clear limitation that should be discussed in chapter 6.

5.1.3 Single Board Computer

The Computational Platform is to be mounted on the drone in such a way as to not obstruct any of the drone's sensors, and ideally minimizing the displacement of the drone original center of mass. This is extremely important because as previously said, the IMU keeps track of its pitch, roll and yam. This metrics should not change with the SBC because it can compromise the hover capability and reliability of the drone. The SBC software housing suggestion is a **Raspberry Pi Zero. Table 5.3** shows a summary of its characteristics.

Table 5. 3 Raspberry Pi zero specifications

Raspberry Pi Zero	
Dimensions	65x30x5mm
CPU	
Clock Speed	1GHz
RAM	512MB
Wireless connection	Compatible with the 2.4GHz 802.11n wireless LAN protocol
SD Card Memory	16GB

A Wi-Fi adapter is required to connect the computational platform to one of several APs via Wi-Fi for the transmission of the computational platform's local database to the main warehouse database. The adapter used is a **TP-Link TL-WN321G 54 Mb/s Wireless USB Adapter**.

5.1.4 RFID Tags

The RFID Tags chosen has to be compatible with the RFID reader. The selected RFID tag are ALN-9662, Higgs-3, ”Short” Inlay type tags[3]. They perform exactly what we expected. They are operated by reader in UHF and comply with the EPC Class 1 Gen 2 protocol.

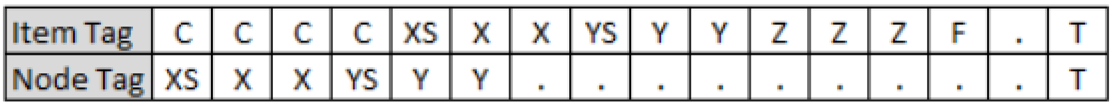
Table 5.4 summarizes the key features of this RFID Tags:

Table 5. 4 RFID Tags Characteristics (adapted from the ALN-9662 technical sheet[3])

Protocols Supported	**ISO/IEC 18000-6C** **EPCglobal Class 1 Gen 2**
Integrated Circuit	Alien Higgs-3
Operating Frequency	840-960 MHz
EPC Size	96 – 490 Bits
User Memory	512 Bits
TID	32 Bits
Unique TID	64 Bits
Access Password	32 Bits
Kill Password	32 Bits

The ALN-9662 Inlay Orientation, Specification, General Dimensions and Stack up should be consulted in the **Attachment 8**

The **symbol distribution** on the tags can be seen on **Figure 5.6**. **C** indicates item count (base 10); **XS** indicates the X-coordinates signal (positive or negative); **X** indicates the X-coordinate; **YS** indicates the Y-coordinates signal (positive or negative); **Y** indicates the Y-coordinate; **Z** indicates the Z-coordinate; **F** indicates the item misplacement flag and is either ”0” (for correctly placed items) or ”1” (for misplaced items), **T** indicates the tag type and is either ”A” (for item tags) or ”B” (for node tags). **A** indicates unused information space.



Item Tag	C	C	C	C	XS	X	X	YS	Y	Y	Z	Z	Z	F	.	T
Node Tag	XS	X	X	YS	Y	Y	.	.	.	.	.	.	.	.	.	T

Figure 5. 3 RFID tag User Memory information storage (adapted from [89])

5.2 Prototype Results

In this section all the results used to build the business case are presented. The prototype build by the student of METI performed some Unit and Functional Tests. Along the section some comments regarding these tests are given and the impact off them in the business case.

1. Unit and Functional Tests

Drone

The DJI Ryze Tello EDU drone performed some unit testing in order to understand its practical limitations. These unit tests were performed while the drone was made to hover in place for 8 minutes

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[3] ALN-9662 Higg-3 RFID Tag Specification: http://www.alientechnology.com/wp-content/uploads/Alien-Technology-Higgs-3-ALN-9662-Short.pdf

while its battery percentage (Figure 5.4), signal-to-noise-ratio to the computational platform (Figure 5.5) and internal temperature (Figure 5.6) were measured.

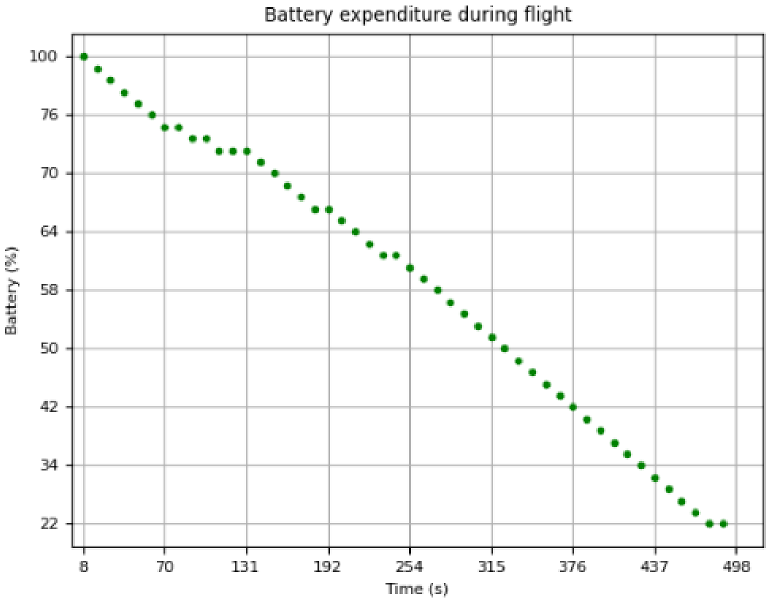

Figure 5. 4 Drone battery expenditure on stationary hover made (adapted from [89])

The horizontal axis represents the time that the drone spent in stationary hover made in seconds (8 to 488) and the vertical axis represents the remaining battery percentage (22 to 100). The flight time and the battery expenditure have a direct proportionality. Over the course of 8 minutes, the drone consumed 78% of its battery life. For safety measures, it was considered that in order to the allow the drone to return to its starting position in safety, that 20% of the battery should be preserved, so that leave us with approximately 78% of battery or 8 minutes to perform a full cycle counting.

Additional tests proved that the drone has an effective flight time of 8 minutes and the drone remains airborne for 10 minutes and 14 seconds.

The drone takes approximately one hour to fully recharge its battery. The flight battery should be fully charged before each flight to avoid erratic and unpredictable behaviour. This limit the amount of flights per day of work to less than ten.

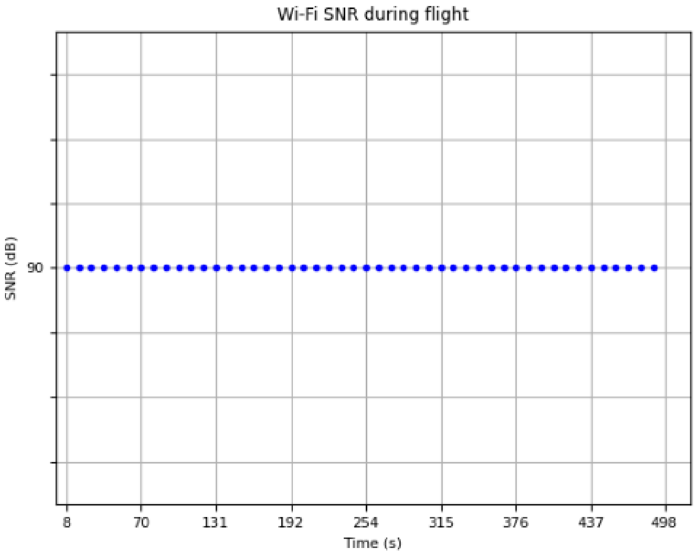

Figure 5. 5 Drone to SBC connection signal-to-noise-ratio on stationary hover mode (adapted from [89])

The horizontal axis represents the time that the drone spent in stationary hover made in seconds (8 to 488) and the vertical axis represents the SNR which remains constant throughout the test. Given that, the SBC and the drone travel together, this is an expected result.

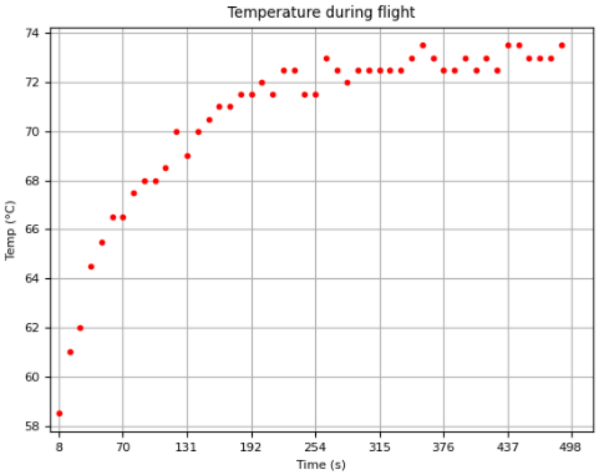

Figure 5. 6 Drone internal temperature on stationary hover mode (adapted from [89])

Once again, the horizontal axis represents the time that the drone spent in stationary hover made in seconds (8 to 488) and the vertical axis represents the drone's chipset temperature in degrees Celsius (58 to 74), averaged from the 3°C interval received in each response. In the first minutes of use, the internal temperature of the drone increases dramatically as expected but then this internal temperature stabilizes at 72°C and 74°C. This increase is partly consequence of the spinning of the blades. The drone has no internal cooling mechanism. The lack of an internal cooling mechanism makes it necessary for the drone to vary the speed of its rotors. This factor cause a delay in the commands sent to the drone and augment error margins. The drone enters a shutdown state once it reaches a critical temperature above 75°C and stops executing commands. Additionally , while testing its main camera and video streaming functionalities, the drone was found to overheat and shut down approximately in one and half minutes.

Regarding the functional tests of the drone, the Vision Positioning System (VPS) of the drone presented major difficulties. Its performance is affected by numerous conditions. The objective of the functional tests was to achieve the practical limitations of the VPS. It is important to remember that the aircraft automatically changes to Attitude mode when the VPS is unavailable. In Attitude mode the aircraft is not able to position itself. It was of interest to know the events' characteristics of when this happen. The events that the drone changed to attitude mode was registered:

- Drone flying at high speed below 0,5m.
- Drone flying over monochrome surfaces.
- Drone flying over highly reflective surfaces.
- Drone flying over moving objects.
- Drone flying in an area where the lighting changes cause disorientation for brief moments.
- Drone flying above 6m.

Without the VPS operating, the all system is useless, so, to obtain good results, the drone was kept a consistent altitude throughout 80% of tests. The height variation on the remaining tests was between 20cm and 1m, to see if the drone can scan in different shelf levels.

Secondly, the functional tests allowed to realize that the drone does not compensate for its speed when stopping after a "move" command whatever its speed. Furthermore, after some weeks of testing, the drone developed a problem with its rear-right motor.

When taking off, the respective propeller was the last to get to full throttle. The rear-right propeller produced a different sound when spinning and its spinning decelerated at a faster rate. It was also the first to stop when landing. The remaining three propellers all started and stopped at the same time. The propellers were replaced, and the problem persisted. The motors were all clean and showed no signs of external wear. The only possible conclusion to be derived from this situation is that the rear-right motor is either faulty or more worn-out than the others. The most direct impact of this problem was a horizontal spinning motion that caused the drone to slowly rotate clockwise at a rate of approximately 0.21°/s. Once issued a "move" command for the drone to move forward 1.47m, the drone would drift right approximately 20cm. The solution for this problem involved experimenting with the average involuntary yaw the drone would pull per second. In **Attachment 11** the situation is exposed in photos and the solution presented. In the end this problem made it impossible to apply the prototype to a real warehouse, for safety concerns.

RFID System

Before performing a full functional test of the system, the RFID system should be programmed in a certain way to mitigate its physical limitations. Is important to remember that in order to maximize read range and signal quality, tags should be placed according to the Size, Orientation, Angle, Placement (SOAP) factors. The SOAP factors should be established before the frequency of the RFID system is tested.

In the unit tests of the RFID System the tag's SOAP specifications are as follow [89]:

- **Size:** The tag is 7 cm wide and 1,7 cm tall.
- **Orientation:** The tag is placed on a vertical surface with its widest sides parallel to the ground.
- **Angle:** The tag is read by the RFID Reader when the front-facing surfaces of both are parallel to each other.
- **Placement:** The tag is placed against a non-metal surface, in this case against the side of a cardboard box.

Two different unit tests were performed. These test's specifications were defined jointly between the author and another student from the MSc in Telecommunications and Informatics.

Firstly, the RFID Reader was placed vertically, with its frontal surface parallel to the tag's frontal surface, facing it. This experiment helped verified the ideal **SOAP** for a tag, the choice of the **best frequency** to use for tags and determined what the **gain** or **power** on the **RFID Reader** should be **set to**. The choice of the best frequency to use was achieved by measuring the maximum read range for each frequency. The results are presented bellow in **Table 5.5**. The power setting o on the RFID Reader was achieved by comparing three different power settings with their effective read range. The results are present bellow in **Table 5.6.** Both tables were adapted from results obtained in [89].

Table 5. 5 Comparison between the available Query Frequencies and their Maximum Experimental Read Range

Frequency Setting (MHz)	Experimental Read Distance
CN2 840~845	1.5 cm
EU 865~868	1,5 cm
US 902~928	22,5 cm
CN 920~925	25 cm
TW 922~928	25 cm

Although the tags were advertised as compatible with European Union frequency ranges (865MHz to 868MHz), the maximum read range testing indicate they operate best in the Chinese (920MHz to 925MHz) and Taiwanese (922MHz to 928MHz) frequency ranges, with some success using the United States frequency (902MHz to 928MHz) as well.

Table 5. 6 Comparison between the minimum, intermediate and maximum power setting, and the Maximum Read Range

Power Setting	Experimental Read Distance
0	7 cm
7	15,5 cm
14	25 cm

The comparison between the minimum, intermediate and maximum power setting, and the maximum read range show that there is a direct relation between maximizing the RFID Reader's power maximized the distance at which it can read the tag.

In order to increase the performance of the RFID reader, the RFID reader was configured to emit queries at the TW frequency setting (922 MHz to 928 MHz) and its gain was set to its maximum value (power setting 14 at approximately (25 dBm). It was with this configuration that the second unit test was conducted.

The RFID was placed at a similarly position as the first test, vertically and with its frontal surface parallel to the tag's frontal surface, facing it. Then the tags were placed at their tallest and afterwards at their widest. The objective of this test was to know the **minimum distance between tags** that the RFID **could read** with **100% accuracy**. The RFID Reader was kept at a 20cm distance from the tags. The minimum distance between tags results are represent on **Figure 6.2.**

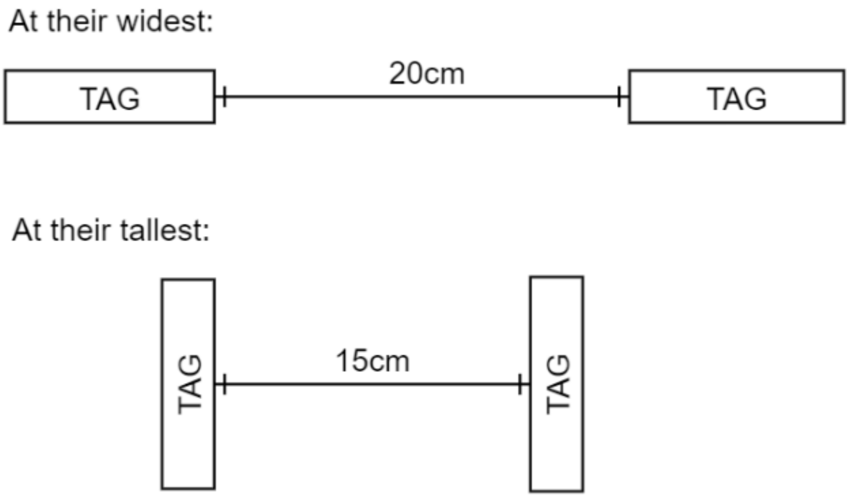

Figure 5. 7 Ideal distance between tags, read from 20 cm away

The results obtained was very influence for the results discussion. It was found that the experimental values for the distance at which to set the RFID tags apart from each other to ensure 100% accuracy impacted, directly depend on the **speed of the drone.** It is important to remember that the **drone** and the **RFID Reader** travel at the **same speed**. Facing **20cm away**, the RFID could only read one tag while the drone fly at a constant **speed** of **20 cm/s**. At their tallest, the RFID Reader could only collect one response from each tag when they were placed at least 8,5 cm apart horizontally. When the tags were set at their widest, a minimum distance of 15 cm was required to achieve the same result. At a speed superior to 20 cm /s the RFID Reader could not read any tag. This result was discovered to be the result of the number of collision in the tag response to each of the RFID Reader's queries when the drone travels faster than 20 cm/s. The number of collisions makes it impossible for the RFID Reader to read the tags. As showed in the figure above, at a constant speed of 20 cm/s, the system composed of the drone and the RFID Reader could read the tags at their **tallest** when they are set **15 cm** apart and only **20 cm** apart when they are at their **widest**.

This experiment allowed to conclude that the drone can only travel at a maximum constant speed of 20 cm/s, the RFID should be placed 20 cm away from tags, and the tags should be placed at their tallest to maximize reading efficiency. In addition, this experiment show that in reality this RFID Reader is **not** able to **read** multiple tags at once through **bulk reading** explained by the collision phenomenon observed in the tag responses. The "Auto Read" button seemed to have no impact on the function to bulk reading as well. This was a major disappointment because the speed at which the drone is limited to 20 cm/s. A better RFID Reader should be implemented.

2. Flying Tests

Numerous flying tests were conducted. The specifications of the drone and the RFID system used were the ones discovered in the unit tests. The limitations identified were mitigated using the tools available, in order to perform the best results possible. The flying tests were conducted utilize an artificially lit room with an area 4m wide, 5,60m long and over 2m tall picture in **Figure 5.8.**

The system was set at a constant speed of 20 cm/s. The UAV system starts the cycle counting was set at coordinate $O_{(0,3)}$. A set of 13 tags were placed horizontally at between twenty centimeters and one and a half meters apart from each other at their tallest to represent items stored along two shelves: between x-coordinates 0 and 1; and between x-coordinates 1 and 2. Some tags were covered by a cardboard piece approximately 1 cm thick. A single shelf level was accounted for when placing the tags. A set of 12 node tags were placed in the floor of the simulated warehouse. Each node tag has a coordinate (x, y). The RFID Reader is carried by hand along with the SBC because, as previously said the drone cannot carry the RFID system. The constant speed of the drone is respected however (20 cm/s). This reader is 20 cm way from the tags. At a constant speed of 20 cm/s the system can read all the tags along the corridor without stopping. Each movement is subject to a delay. This delay was observed to be the result of the "move" command. This "move" command issued by the communication component is not always accepted by the drone at the first time. For that reason, this component issues attempts this command six times with three seconds of time spacing between each attempt, until de drone accepts the "move" command. Worst case scenario, the "move" command is accepted on the fifth attempt, which causes a delay of 18s (3s times 6 attempts). Best case scenario, the "move" command is accepted on the first attempt, which causes a delay of 0s. This **delay** can be **observed** on the **video** on the footnote[4].

In the flying tests, the time it takes the system to perform the cycle counting can be described by the following steps:

1. The drone was facing North, so it had to turn **180° to advance** to node $\mathbf{O_{(0,2)}}$**.** This **movement** command is called ***RTT***. In the flying tests, this command **took**, on **average**, **2s** to be performed. The "**move**" **command** was **accepted** on **average** on the **second** attempt. In total this command comprises, on average, a **total** of **8s** (RTT movement (2s) + "move" command (2 attempts, 3s each)). In **total**, the drone **makes** this **move five times**: on node (0,3), (0,0), (1,0), (1,3) and (2,3)

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[4] https://photos.app.goo.gl/gGk1JUE7nkkijFyYA

2. After **rotating**, the drone can **travel** to node **$O_{(0,2)}$.** The **movement from one** node to **another** is called **Forward Moving Vertical or *FWD_Vertical*.** In **forward** moving vertical, the **drone travels** at a constant **speed** of **20 cm/s**. The **distance between nodes** is **147cm**. In the flying tests, this movement **took**, on **average**, **7,35s** ($\frac{147cm}{20cm/s}$) to be **performed**. The "move" command was **accepted** on average on the **second attempt** as well. In **total** this command comprises, on average, a total of **13,35s**. **This movement** is **done three times** in **each corridor**. In the first corridor this movement is from node (0,3) to (0,2), (0,2) to (0,1) and (0,1) to (0,0). In total, this forward moving takes 40,05s in one corridor.

3. After the system reaches the node (0,0) it has to **adjust its trajectory**. This **command** is **done** by the **navigation component** and it is called ***ADJ.*** In the flying tests, this command **took**, on **average**, **30s** to be **performed**. The "move" command was **accepted** on **average** on the **first attempt**. In **total** this command comprises, on average, a total of **33s** (ADJ movement (30s) + "move" command (1attemp, 3s each)). In **total**, the drone **makes** this **course correction** movement **two times**: on node (0,0) and (1,3). The course correction made on node (2,0) is **not considered** to be **part** of the cycle count activity.

4. After performing the course correction, the system travels to node (1,0), in order to **scan** the **second corridor**. The movement **from one** node to **another horizontally** is called **Forward Moving Horizontal or *FWD_Horizontal*.** In forward moving **horizontal**, the drones **travels** at a **constant speed** of **20 cm/s**. The **distance** between **horizontal nodes** is **100cm** or **1m**. In the flying tests, this movement **took**, on average, **5s** ($\frac{100cm}{20cm/s}$) to be **performed**. The "move" command was **accepted** on **average** on the **second attempt** as well. In **total**, this command comprises, on average, a total of **11s**. In **total** the drone **makes** this **move two times**: (0,0) to (1,0) and (1,3) to (2,3).

Based on the description above, the time it takes the system to perform the cycle counting can be computed by as follow:

$$\begin{aligned} &TimeCycleCount\ (s) \\ &\quad = \left(3\ FWD_{Vertical}(s) \times Nº\ Corridor\ (\#)\right) + (5\ RTT)\ (s) + (2\ ADJ)\ (s) \\ &\quad + (2\ FWD_{horizontal})(s) \end{aligned} \tag{14}$$

Based on the flying tests, the Total Time the system takes to perform the cycle counting was, on average:

$$TimeCycleCount\ (s) = (3\ \times 13{,}35 \times 3) + (5\ \times 8)\ + (2\ \times 33) + (2 \times 11) =\ 248{,}15s$$

This means that the drone can scan all the items in approximately **4,14 minutes** or **0,07 hours.** It takes **1,38 minutes** or **0,023 hours** to do **one corridor** This was a great result because as previously said, the system only has approximately 8 minutes to perform the cycle counting. It is important to highlight that this cycle counting was not performed considering the shelf levels because to obtain good results the drone was kept a consistent altitude throughout the flying tests. In a real warehouse shelfs have different levels, so it is important to solve the VPS's problems to obtain the Total time of the cycle counting for shelf levels as well. Additionally, in these flying tests, 13 item tags per shelf were used, but in reality, we can place as many tags as we want, as long as we respect the distances highlighted in Figure 6.2.

During the flying tests, the performance of each component was satisfactory. Each component executed its tasks correctly with minimum time of execution. The only exception was the problem presented on Attachment 11. The resolution applied could not prevent the problem with the rear-right motor of the drone. At the end of the cycle counting, the drone was roughly 2m off-course with a 45° of incorrected yaw error. The final results were greatly affected by this problem. In case this prototype has been adapted to a real case the drone would have hit the shelves. Regarding the inventorying and communications components, the local database was correctly accessed by the communications and inventorying components, the RFID interface controller correctly parsed the Wireshark capture file and obtained the scanned items' tag information. In case that some obstacles were placed in front of the tags, the RFID had no problem scanning the items' tag information, unless the obstacle is made of metal. Additionally the local database was populated beforehand with record of 13 items. Between them, were misplaced products on purpose to see if the RFID system could locate misplaced items. The inventorying component correctly update the item tag information and issued a flag of 1, indicating that the item was misplaced. **Attachment 12** can be consulted to observe the output excerpt of the local database for this experiment. The computational time of each component to perform its tasks is very small, so we can conclude that the drone obtains the information in near real time.

Despite all the shortcomings exposed by the tests, the UAV RFID based system build by the student of METI to perform the cycle counting, work as a valid proof of concept. This proof of concept is a realization that a UAV RFID based system has practical potential to perform cycle counting. The performance metrics should not be taken harshly because the system is flawed in some way and only work as a proof of concept. Nevertheless, this performance metrics obtained by the student of METI were the utilize to construct the business case.

5.3 Business Case

The proposed methodology developed for the creation of the business case begins with the identification of benefits. As previously said, not all opportunities for improvement, identified on section 4.3, will be a reality for all companies that adopt the proposed prototype. Ideally, this prototype should have been applied a real case. This application would allow for interviews with "cycle counters" to understand to what extent the tasks they perform daily will be affected with the introduction of drones and to identify the actual opportunities for improvement. Being a proof a concept with a lot of functional issues (stated in section 5.2), we were **unable** to **apply** the **prototype** to a **real warehouse**, for safety concerns. To **simulate** a **real warehouse**, we utilize an **artificially lit room** with an area **4m wide**, **5,60m long** and over **2m tall** picture in **Figure 5.11**. The **warehouse layout** consists of a grid of **three** nodes (x-axis) by **four** nodes (y-axis). In other words, this mock-up represent a storage area with **three corridors** and **four single deep pallet racking shelfs**.

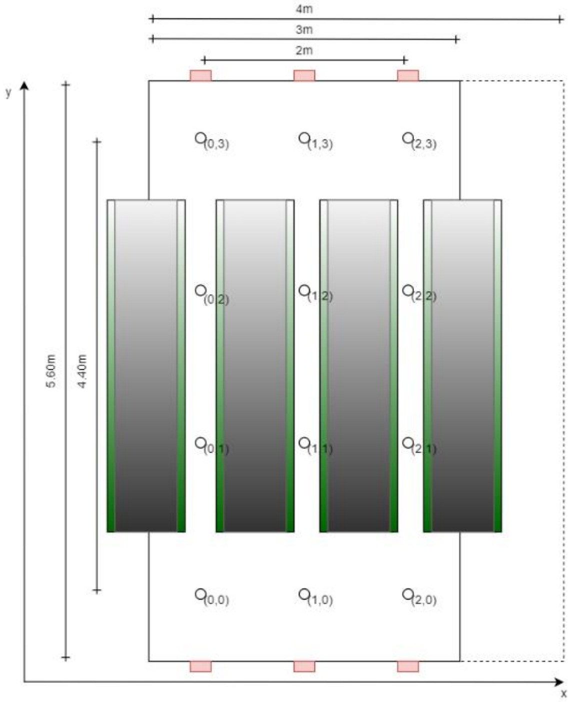

Figure 5. 8 Warehouse Layout Mock-up (adapted from [89])

The data required to quantify the benefits was obtained by exposing the drone to different scenarios within the room. In all the test the drone's starting position was the coordinate set (0,3). To scan the item tags, the drone moves node to node without stopping and correct its position at coordinate set (0,0), (1,3) and (2,0). The necessity to simulate a warehouse environment through this artificially lit room, inhibits a deeper analysis of the possible benefits. Figure 5.9 depict the benefits that can be quantified under these conditions. This figure allows us to conclude that 3 of the 9 quantitative benefits identified on Figure 5.9, do not apply under these circumstances. The explanation of the reasons is given below Figure 5.9.

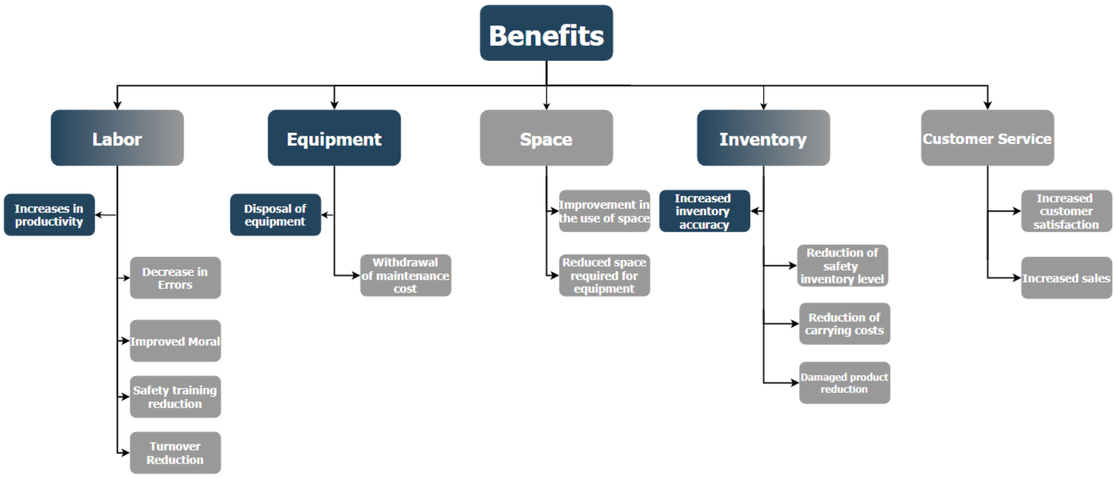

Figure 5. 9 Updated benefits resulting from the automation of the cycle counting activity using drones

Evaluating the Figure 5.9 and Figure 4.9, we can see that all the qualitative benefits remained but some of the quantitative turned to qualitative. This difference, does not mean that this benefits cannot be quantified, this only means that, within the environment that the drone was tested it was either difficult to quantify the decrease or increase of certain benefit or it was rather impossible with the resources at hand. A note should be made regarding the “Decrease in errors” benefit. Although a literature review conducted allowed to check that most of the information is already integrated into the system by the “cycle counters” using barcode scanners, this only account for one of the errors that the “cycle counters” do, therefore it is sill expected that the adoption of drones will reduce the errors that occur during the cycle counting, namely: wrong quantity or product taken to fill an order, stock placed in wrong bin and UOM misinterpreted. However, in the literature the costs of correction this type of errors as yet to be studied so it was not possible to quantify this saving. Nonetheless the system showed perfect results regarding this topic. In the new system the information is automatically inserted by the database component.

Regarding the equipment benefits, although it was impossible to simulate the cycle counting using forklifts to elevate people in order to count the highest level of the warehouse, it is understood that people need this type of equipment to achieve higher levels. Also it was not possible to find the withdrawal of maintenance cost. With respect to space related benefits, the two benefits presented in Figure 4.9, appear in Figure 5.9 as qualitative benefits because it was only possible to utilize the room as a tiny storage area, thus it is difficult to quantify the improvement in the use of space, so this benefit is classified as qualitative. In addition, warehouses have a dedicated space to store the equipment used, therefore the adoption of drones in the cycle counting activity would not manifest itself in an increase in the space to store new products. Nevertheless, this will be quantitative benefits if the proposed system can reduce the safety inventory level and should be quantified for a real business case. Finally, regarding the inventory related benefits, it was only possible to quantify the inventory accuracy. Given that we are not applying the system to a real case, the value of the inventory were going to be arbitrary, so the analysis was not going to offer greats insights, so it was discarded.

Once the benefits have been identified and classified (under these circumstances), it is necessary to quantify the savings. To achieve that, the hardware performance and the software performance metrics of the drone have to be explicit. Bellow, this performance metrics and additional necessary data is divided into the categories identified in Figure 5.8. These performance metrics were obtained through unit tests, functional tests and components tests of the drone inside the room.

1. Benefits Related to Labor

Increases in productivity

On section 4.4 it was stated that the system will perform the cycle counting without human intervention, so the direct and indirect labor will be completely replaced. The results obtained in section 5.2 show that the system is autonomous. The functional tests showed that the system is autonomous and do not require any human intervention.

In the next chapter of results discussion, the main results should be obtained by applying this data and the expression (4) and (5).

2. Equipment Related Benefits

Disposal of equipment

To perform the cycle counting it was considered that the cycle counter utilized at least a barcode scanning technology and a forklift work platform to elevate workers. Cycle counters can utilize numerous barcode scanning technology. In this dissertation three systems were considered[5]:

- Mobile computers with integrated scanners (Motorola MC9190-G) with a price of 2 042,66 €.
- Handheld barcode scanner technology (Wasp WLR8950) with a price of 121,30 €.
- Mobile barcode scanning app (Fleetio Parts) that is free for Fleetio users

Regarding the forklift work platform, the rental price per day is 57 € and the purchase price is 1 169,86 €[6].

All photos and specifications of the equipment can be consulted on Attachment 10.

4. Inventory Related Benefits

The inventory accuracy is calculated by using data from Table 5.5 and the following expression:

$$Inventory\ accuracy = \left(1 - \frac{|WMS - QtyCounted|}{WMS}\right) \times 100\ \% \tag{15}$$

Table 5. 7 Inventory Data

Inventory	WMS (€)	QtyCounted (€)	Discrepancy (€)	Accuracy (%)

In addition, to compute this inventory accuracy we have to know if the system can identify the discrepancy between the quantity on the shelf and the on-hand quantity in the WMS. This performance metric is connected to the hardware and software performance. The performance of the hardware was evaluated by conducting unit test of the RFID System to see if the system could scan the identification tags. Several experiments were done and are detailed and discussed in chapter 6. In short, the RFID tag reader indeed can scan the RFID Tag information. In the other hand the performance of the software

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[5] https://www.fleetio.com/blog/cost-comparison-barcode-scanning-technology ; Last consulted November 25, 2020.

[6] https://shop.andersonrentals.com/products/forklift-work-platform ; Last consulted November 25, 2020.

is also very important to eliminate the discrepancy between the quantity on the shelf and the on-hand quantity in the WMS. It is important to remember that the inventory level that is registered in the WMS is recorded in real time. To state that there is no discrepancy between the on-hand quantity in the WMS and the inventory level on the shelf the inventorying component has to update the warehouse database in near real time.

The performance of this software was very important because it is expected that drones can act as sensor platforms to acquire the near real-time data, a key requisite to achieving Warehouse 4.0. The good news was that the system performed better than expected **taking less than three seconds** to scan the tags**.** Thus, it is plausible to state that if the hardware part of the system can scan the item tags with 100% accuracy, the software can update the warehouse database in near real time.

5.3 Chapter conclusions

The purpose of this section was to explain the way in which the data used to build the business case were obtained by the student of METI. The data obtain via experiments and tests is to be used in chapter 6 in the results section to build the business case. All the data presented in this chapter were obtained exposing the prototype to defined scenarios build in partnership with the the author and another student from METI.

Firstly, the implement architecture was presented on section 5.1 and can be summarized as follow: an UHF RFID Reader (WRD-130-U1) is carried by a DJI Ryze Tello EDU drone. Regarding the used RFID tags, we choose the ALN-9662 tags. The RFID card reader is connected through a TP-Link Wireless USB Adapter to a Raspberry Pi Zero. The item tag information contained in the ALN-9662 tag, is first storage in the local storage of the Raspberry Pi Zero and then sent through Wi-Fi to the warehouse database, that is run in the laptop of the MSc student in Telecommunications and Informatics. Afterwards, each subsystem implemented was characterized (UAV, RFID Reader, SBC and RFID Tags). Along this section the necessary specification, requirements and simplification strategies were explained for each subsystem.

Secondly, the experiments and tests to acquire the data required to quantify the benefits, were obtained by exposing the drone to different scenarios within the room. The desired outcome of the tests was the hardware and software performance and its limitations.

Thirdly, the reasons why we were unable to apply the prototype to a real warehouse were presented. These issues relate to safety concerns. An alternative to simulate a real warehouse is presented. This alternative consists of a storage area with three corridors and four single deep pallet racking shelfs. The room has an area 4m wide, 5,60m long and over 2m tall picture in Figure 5.7. The data required to quantify the benefits was obtained by exposing the drone to different scenarios within the room. This simulation inhibits a deeper analysis of the possible benefits. Six of the nine quantitative benefits do not apply under these circumstances. The explanation related to this topic was given.

Finally, once the above benefits were identified, we proceed to quantify them. To achieve that, the hardware performance and the software performance metrics of the drone were explained. These explanations were divided into the categories identified in Figure 5.8. The data required were obtained through unit tests, functional tests and components tests of the drone inside the room.

6. Results Discussion

In this chapter, the main results obtained by applying the data referred to in Chapter 5 to each step of the methodology proposed in Chapter 4 are presented. The results presented comprise the savings estimation, cost estimation and economic justification. This application is made considering the experiments presented and the limitations of the system.

6.1 Business Case

This section presents the results achieved by applying the data obtained in section 5.2. and 5.3. The results presented comprise the savings estimate, the cost estimate, and the economic justification. As previously said the major realization of a certain proof of concept is to demonstrate **its feasibility**, not their **economic viability**. Given the circumstances, the savings estimation, costs estimation and economic justification should be interpreted lightly. In other words, this estimation is used to demonstrate the potential of the system instead of a robust business case. Most of the data is used to compare the performance of the system presented in section 6.1. A time horizon was not used because its not suit the economic justification strategy explained in section 4.6. The business case were constructed based on the performance of the prototype on the environment of figure 5.11.

6.1.1 Savings Estimate

Increases in productivity

The system showed to be able to perform the cycle counting without human intervention so the direct and indirect labor will be completely replaced. In the simulated warehouse it is only possible to analyze the performance of the direct labor or cycle counters. So, according with expression (5) it is needed to know the number of FTEs saved. The room was small so only one “cycle counter” was simulated. He/she was equipped with a virtual barcode scanning. It is considered that the **speed** of the “cycle counter” was **4 km/h** and they take an average of **10** seconds to **count** a **bin location**, **10 seconds** to **count** an **empty pallet**, **3 minutes** to **count** a **half pallet** and **6 minutes** to count a **full pallet**. This numbers were based on empirical evidence. The average hourly wage for a Cycle Counter is **20€.** In each corridor the “cycle counter” had to **count 26 tags** that correspond to **26 products** (13 tags per shelf on both sides of the corridor). The time it took to count these products are presented on Table 6.1.

Table 6. 1 Time spend doing the cycle counting by humans

Scenarios	**Unit Economic: Time** **Time spend doing the cycle count per corridor (h)**	**Total Time Spend doing the cycle count (extrapolation for 3 corridors) (h)**
1. Full pallet	**2,6**	7,80
2. Bin locations	**0,07**	0,22
3. Half pallet	**1,3**	3,90
4. Empty pallet	**0,07**	0,22
5. 50/50 full pallet and half pallet	**1,95**	5,85
6. 50/50 full pallet and empty pallet	**1,33**	4

The “cycle counter” travels at 4km/h or 111 cm/s. The corridor is 440cm long. He/she stops thirteen times to count the items of each shelf. In total he/she counts 26 items. The numbers in the *Unit*

Economic: Time column are not very useful; is the logic behind the unit economic that give context and relevance to these numbers. Every Unit Economic is referred to a performance metric in a corridor (e.g. the Unit Economic Time correspond to the time spend doing the cycle count per corridor).

The scenarios analysed were not random. The breadth of the scenarios thought aim to represent different parts of the warehouse. The first scenario aims to represent the section of a warehouse in where the products are fully stored in pallets (C and D products). These products are stored in pallet for many reasons or are slow movers. In this scenario, the "cycle counter" **takes 2,6 hours** per corridor and **7,80 hours** in total. This is not critical because these areas are counted 1 or 2 time per year. The second, third and fourth scenarios aims to represent sections of a warehouse that are close from the outbound (A and B products). Picking zones or replenishment zones. For bin locations and empty pallets, the "cycle counter" takes **0,07 hours per corridor** and **0,22 hours in total**. These locations normally are counted more times per year (3 to 6). Thus, although it seems like a short time per corridor, if we account that this process is done six times a year, the savings could be astronomical. The last two scenarios were done to simulate areas of the warehouse were the two storages types coexist. In contrast the UAV RFID system is agnostic to the storage type. This mean that the system scans all 26 products, for all scenarios in 0,07 hours in total and 0,023 hours in total (4,14 minutes and 1,38 minutes respectively). **Table 6.2** highlights the savings in time between the drone and the "cycle counters". However, the savings in time are not used to calculate the savings in money. The savings in money result from the reduction in labor using the expression (5). The **cost per worker** is **substituted** by the **average hourly wage** for a **Cycle Counter** and the **labor FTEs** are **substituted** by the **data** from **Table 6.1. Table 6.3** show the savings related form the increase in productivity.

Table 6. 2 Time Performance. Drone vs. "Cycle Counters"

Scenarios	**Human Unit Economic: Time (h)**	**Drone Unit Economic: Time (h)**	**Unit Economic: Discrepancy (h)**	**Human Extrapolation for 3 corridors (h)**	**Drone 3 corridors (h)**	**Discrepancy 3 corridors (h)**
1. Full pallet	2,6	0,023	**2,577**	7,80	0,07	7,6
2. Bin locations	0,07	0,023	**~0,047**	0,22	0,07	~0,15
3. Half pallet	1,3	0,023	**1,277**	3,90	0,07	3,83
4. Empty pallet	0,07	0,023	**~0,047**	0,22	0,07	~0,15
5. 50/50 full pallet and half pallet	1,95	0,023	**1,927**	5,85	0,07	5,78
6. 50/50 full pallet and empty pallet	1,33	0,023	**1,307**	4	0,07	3,93

Table 6. 3 Savings Estimate | Increases in productivity

Scenarios	**Human** **Unit Economic: Time (h)**	**Average hourly wage (€)**	**Unit Economic:** **Savings per corridor (€)**
1. Full pallet	2,6	20	**52**
2. Bin locations	0,07	20	**1,4**
3. Half pallet	1,3	20	**26**
4. Empty pallet	0,07	20	**1,4**
5. 50/50 full pallet and half pallet	1,95	20	**39**
6. 50/50 full pallet and empty pallet	1,33	20	**26,6**

Two examples are given of how the **reader** of this dissertation **should interpret** the **Unit Economic results**.

Scenario 1: Corridors with only Full Pallets (Unit Economics at Red in the Tables)

The UAV RFID system offer the opportunity to replace completely the direct labor. Thereby, if we consider that this area of the warehouse, should be cycle counted **one time** per **year**, we can interpret the results as follow. For a corridor of **4,40m** with **26 pallets to be counted**, a company can replace **2,6 hours of work**, get the **information** about **inventory level 2,577 hours earlier** and **save** in the process, **52€.**

Scenario 2: Corridors with only Bin Locations (Unit Economics at Green in the Tables)

The UAV RFID system offer the opportunity to replace completely the direct labor. Thereby, if we consider that this area of the warehouse, should be cycle counted **six times** per **year**, we can interpret the results as follow. For a corridor of **4,40m** with **26 bin locations to be counted,** a company can replace **0,07 hours** of work, **times six times** per **year,** get the **information** about **inventory level 0,047 hours earlier** and **save 1,4€ , times six events** per **year.**

Although the results on itself does not offer the opportunity to build a robust Business Case, the Unit Economics strategy offer an opportunity to the reader to apply the same logic to its warehouse layout using the reasoning of the examples and extrapolating the results.

Disposal of equipment

The study conducted in Chapter 4 and 5 puts in correlation the disposal of equipment with the reduction of the labor. In fact, the experiments conducted, showed that the system behave autonomously without human intervention. In a real case, the expressions of the proposed methodology and the data about the equipment could be applied. In the case of this dissertation, given that the “cycle counter” is completely replaced the logic is different. Only one “cycle counter” was simulated. It is assumed that to perform this cycle counting he/she needed a barcode scanning technology and a forklift work platform. With the replacement all the barcode scanning technologies and forklifts work platform would disappear. Regarding the integrated scanners, the results showed that, for all 6 scenarios the utilization of this product is minimum, therefore there is no need to sell the device.

As for the forklift work platform, as there is the possibility of renting the equipment, the savings will vary with how many counts a certain section of the warehouse has. If we consider the two examples above, the forklift had to be rented only one day for the pallet section and six days for the bin's locations. That is, the number of counts per year is equal to amount of days that the equipment has to be rented. In the disposal of equipment, the Unit Economic is rental days. Remember that a Unit Economic is referred to a performance metric in a corridor. The performance metric is this section, is the rental days.

Table 6. 4 Savings Disposal of equipment

Scenarios	**Number of counts per year (#)**	**Rental Price** **(€)**	**Unit Economic:** **Savings per corridor (€)**
1. Full pallet	1	57	**57**
2. Bin locations	6	57	**342**
3. Half pallet	4	57	**228**
4. Empty pallet	6	57	**342**
5. 50/50 full pallet and half pallet	3	57	**171**
6. 50/50 full pallet and empty pallet	3	57	**171**

Considering the data on Table 6.1 and 6.4, even if we combine the time spend doing the cycle count per corridor of all the scenarios this does not correspond to a full day of rental. Thus, we can conclude that we can rent the forklift only 6 times per year to perform the cycle count of A products and use the free time to perform the other cycle counts for B, C and D products.

The **reader** of this dissertation **should interpret** the **Unit Economic result** as follow: The UAV RFID system offer the opportunity to replace completely forklift. Previous to the introduction of the UAV RFID system, for a corridor of **4,40m** with **26 pallets to be counted**, a company has to rent a forklift 6 times in a year in order to perform all the scenarios. The system saves at least **342€** to the company.

Inventory Accuracy

As previously said, the system performed better than expected and since the scan of the RFID tag and the update of the tags.db, the system **takes less than three seconds.** In the flying tests the system was able to identify misplaced items and update the warehouse database as seen in attachment 12. These results indicate that the proposed UAV system delivered a 100% inventory level accuracy in near real-time. Unfortunately, the impact of this accuracy in the reduction of safety inventory levels and carrying costs was not possible. Ideally, these benefits should be quantified comparing the improvement with just the WMS and then the WMS plus UAV system to see the impact of having near real time inventory level information has on the reduction of safety inventory levels.

6.1.2 Costs Estimate

Total Cost of the System was 340€. The drone is the DJI Ryze Tello EDU (160€). The RFID is an UHF RFID Reader (150€). Regarding the RFID tags, we choose the ALN-9662 tags. These tags came in packs and each pack cost 30€. We use a laptop to perform the tasks of the SBC. Additionally, all the software used is open source.

Table 6. 5 Cost Estimate of the proposed UAV RFID System

	Cost (€)
Hardware	
UAV	160
Tag Reader	150
SBC	0
Identification tags	30
Software	
Communications Component	0
Navigation Component	0
Inventorying Component	0
Local Storage	0

6.1.3 Economic Justification

The next step in the methodology is to translate the performance of the UAV RFID based system into an economic justification. This economic justification does not involve calculating the NPV or the Payback Period, because these type of economic justification does not apply to a proof of concept. Instead the economic justification of a proof of a concept should demonstrate the inner potential of the system through its unit economics. The main objective of this section is to clarify if the proposed system presented in the methodology, actually delivered the benefits that were stated in the business case. Firstly, superficially speaking, the main hopes for the system was that, inventory counting could be reduced to hours instead of months, 100% inventory accuracy in near real-time was possible and overall safety of operations could be dramatically improved. As demonstrated in section 6.1, the system delivered all the above hopes. The main insight for the economic justification was obtained comparing the performance of the new system with the old system. Each benefit was decomposed in unit economics to see how much was gained each time the new system performs the work that otherwise was performed by the old system. Considering the data from Table 6.2, implementing the system has no downside to it. In all the scenarios the system performed equal or better in terms of time to perform the cycle counting. In the first and fifth scenario the discrepancy is high. Each time the new system performs the cycle counting, the company saves the average hourly wage of the worker. The savings seem to be small but is important to remember that every Unit Economic is referred to a performance metric in a corridor with 26 items. In a huge warehouse these savings can be massive. Additionally, the unit tests performance, showed that the system is capable of scanning the tags with 100% accuracy, identified misplaced items and update the warehouse database in near real time. The system is autonomous, so the overall safety of operations will dramatically improve. The system is very cheap overall.

In short, the Unit Economics of the drone while performing the cycle count activity are very promising and the system has huge potential.

7. Conclusion and Future Work

This dissertation had as main objective the creation and evaluation through a business case of a prototype of a UAV RFID based system solution aimed to perform inventory management and inventory traceability. This objective was established after the literature review allowed us to conclude that, although UAV have been a studied topic towards Warehouse 4.0, there is few detailed business cases constructed around the performance of UAVs for inventory management, especially with RFID technologies. For this reason, the first part of the methodology consisted of an analysis find the highest use case potential for the use of drones in warehouses. The North Star Metric Framework was used to conduct this analysis in two layers. In the first layer, to decide between Intra-logistics, Inventory Management, and Inspection Surveillance and the second layer to decide between a handful of activities related to inventory Management. The framework used helped to choose Inventory Management field as the most promising field and the cycle counting activity as the highest potential use case for the use of drones in warehouses. The second part of the methodology consisted of an extensive description of the processes that occur today in the cycle count, in order to identify the current limitations of these processes. With the information gathered in this step, we were able to present the proposed design of the UAV based system prototype aimed to perform cycle counting.

Finally, after the use case was identified and the prototype presented, it was possible to identify the various benefits (quantitative and qualitative) that were expected to arise with the investment on drones to do the cycle counting activity. The set of quantitative benefits include increases in productivity, disposal of equipment, improvement of the use of space and increased inventory accuracy, among others. The qualitative benefits identified were, among others, an improved moral, lower turnover rate of employees and increased customer satisfaction. In addition to the benefits, a set of costs for the construction of the proof of concept were identified. The economic justification strategy used was different from most cases where the NPV and Payback Period are the most common options. The main reason for using a different strategy, was the fact that the prototype developed between the author and another student from the MSc in Telecommunications and Informatics, be a proof of concept. The major realization of a certain proof of concept is to demonstrate its feasibility, not their economic viability so, the NPV or Payback Period do not suit the dissertation's business case. The strategy chosen was to do an economic justification related to a use case proof of concept. This approach removes the importance to established time horizons, because it assumes that there is too much uncertainty about the project to estimate good values of Cashflow along that years. Instead it looks for how much is gained each time the new system performs the work that otherwise was performed by the old system.

To explain the way in which the data used to build the business case were obtained, the implement prototype build the student of METI was presented. This system can be summarized as follow: an UHF RFID Reader (WRD-130-U1) is carried by a DJI Ryze Tello EDU drone. Regarding the used RFID tags, it was chosen the ALN-9662 tags. The RFID card reader is connected through a TP-Link Wireless USB Adapter to a Raspberry Pi Zero. The item tag information contained in the ALN-9662 tag, is first storage in the local storage of the Raspberry Pi Zero and then sent through Wi-Fi to the warehouse database, that is run in the laptop of the MSc student in Telecommunications and Informatics. The UAV RFID based system has to have four main components incorporate, namely: Inventorying component, navigation component, communications component, and a local database. Unfortunately, for safety concerns, the prototype was unable to be tested in a real warehouse environment. This made it very difficult to quantify the benefits. In future work, the system should be applied to a real warehouse environment. The alternative to simulate a real warehouse was to adapt a room (with an area 4m wide, 5,60m long and over 2m tall), so that it looked like a storage area with three corridors and four single deep pallet racking shelfs. These circumstances inhibited a deeper analysis of the possible benefits. Six of the nine quantitative benefits do not apply under the simulated warehouse.

Although the software and hardware will be built by the student of METI, the collected information on 4.2.1 were important to define the structure of the proof of concept. The goal of this dissertation was to use the results of the prototype build by the student of METI and applied them to a business case. The results of the prototype was acquired by running experiments and tests in order to quantify the benefits. The desired outcome of the tests perfomed by the student of METI was the hardware and software performance and its limitations.

The prototype build by the student of METI performed some Unit and Functional Tests. The data used in this desertion

The DJI Ryze Tello EDU drone performed some unit testing in order to understand its practical limitations. The drone's battery has an effective flight time of 8 minutes to perform the cycle count, and the drone remains airborne for 10 minutes and 14 seconds. The battery percentage and the time have a direct proportionality. The drone takes approximately one hour to fully recharge its battery. This limit the amount of flights per day of work to less than ten. The drone to SBC connection SNR remains constant throughout the test. In the first minutes of use, the internal temperature of the drone increases dramatically as expected but then this internal temperature stabilizes at 72°C and 74°C. While testing its main camera and video streaming functionalities, the drone was found to overheat and shut down approximately in one and half minutes. The critical temperature of the drone is 75°C. The functional tests showed that the VPS of the drone presented major difficulties. Among others, the biggest difficulty was the change in altitude that triggered the Attitude mode. In Attitude mode the aircraft was not able to position itself. To obtain good results, the drone was kept a consistent altitude throughout 80% of tests. This made it impossible to test the scanning in different shelf levels. Furthermore, the functional tests allowed to realize that the drone does not compensate for its speed when stopping after a "move" command whatever its speed. Two weeks after the testing phase began, the drone developed a problem with its rear-right motor. The most direct impact of this problem was a horizontal spinning motion that caused the drone to slowly rotate clockwise at a rate of approximately 0.21°/s. A solution was developed but the problem persisted, so the only possible conclusion to be derived from this situation is that the rear-right motor is either faulty or more worn-out than the others. The RFID Reader is carried by hand along with the SBC because, the drone cannot carry the RFID system. In future work a different drone should be chosen.

The RFID system also performed some unit testing in order to be programmed to maximize read range and signal quality. Two different experiments were performed. The first experiment helped verified the ideal SOAP for a tag, the choice of the best frequency to use for tags and the gain of the RFID Reader. The SOAP specifications were established: Size (7cm wide and 1,7cm tall); Orientation (tag placed on a vertical surface with its widest sides parallel to the ground); Angle (front-facing with the RFID); Placement (against a non-metal surface). The performance of the RFID reader was maximized when the RFID reader was configured to emit queries at the TW frequency setting (922 MHz to 928 MHz) and its gain was set to its maximum value (power setting 14 at approximately (25 dBm). The objective of the second test was to know the minimum distance between tags that the RFID could read with 100% accuracy. This experiment allowed to conclude that the drone can only travel at a maximum constant speed of 20 cm/s, the RFID should be placed 20 cm away from tags, and the tags should be set 15cm apart when placed at their tallest to maximize reading efficiency. In addition, this experiment show that in reality this RFID Reader is not able to read multiple tags at once through bulk reading explained by the collision phenomenon observed in the tag responses. In future work a different RFID should be chosen to performed bulk reading.

Afterwards, some flying tests were conducted to know how fast the system can perform the cycle counting and the success rate of its scanning while doing it. A "move" command delay was observed. Worst case scenario the "move" command causes a delay of 18s and best-case scenario the "move" command on the first attempt. Based on the flying tests, the total time that the system takes to perform the cycle counting was, on average 248,15 seconds. During the flying tests each component executed its tasks correctly with minimum time of execution. The computational time of each component to perform its tasks is very small, so we can conclude that the drone obtains the information in near real time. However, the finals final results were greatly affected by the problem of the rear-right motor. At the end of the cycle counting, the drone was roughly 2m off-course with a 45° of incorrected yaw error. In case that some obstacles were placed in front of the tags, the RFID had no problem scanning the items' tag information, unless the obstacle is made of metal. Additionally, the local database was populated beforehand with record of 13 items. Between them, were misplaced products on purpose to see if the RFID system could locate misplaced items. The inventorying component correctly update the item tag information and issued a flag of 1, indicating that the item was misplaced. Despite all the shortcomings exposed by the tests, the UAV RFID based system build in order to perform the cycle counting, work as a valid proof of concept.

In the business case part, a breadth of the scenarios were thought to represent different corridors of a warehouse. In each corridor the “cycle counter” had to count 26 tags that correspond to 26 products. The corridor is 4,40m long. The first scenario aims to represent the section of a warehouse in where the products are fully stored in pallets (C and D products). In this scenario, the “cycle counter” takes 2,6 hours per corridor. The second, third and fourth scenarios aims to represent sections of a warehouse that are close from the outbound (A and B products). Picking zones or replenishment zones. For these sections, the “cycle counter” takes 0,07 hours per corridor. In contrast the UAV RFID system is agnostic to the storage type. It takes 0,023 hours to scan a corridor. For a corridor with Full Pallets, a company can replace 2,6 hours of work, get the information about inventory level 2,577 hours earlier and save in the process, 52€. For a corridor of 4,40m with 26 bin locations to be counted, a company can replace 0,07 hours of work, times six times per year, get the information about inventory level 0,047 hours earlier and save 1,4€ , times six events per year. Regarding the disposal of equipment, the UAV RFID system offer the opportunity to replace completely a forklift. Previous to the introduction of the UAV RFID system, a company has to rent a forklift 6 times in a year in order to perform all the scenarios. The system saves at least 342€ to the company. As for the inventory accuracy, the results indicate that the proposed UAV system delivered a 100% inventory level accuracy in near real-time. The prototype costed 340€ in total. All software is open source. Additionally, the unit tests performance, showed that the system is capable of scanning the tags with 100% accuracy, identified misplaced items and update the warehouse database in near real time. The system is autonomous, so the overall safety of operations will dramatically improve. The system is very cheap overall. The Unit Economics of the drone while performing the cycle count activity are very promising and the system has huge potential.

As a final note, the present work is expected to be a useful tool to encourage future implementations of drones in the cycle counting activity.

References

[1] Eurostat Labour Force Survey, 2016 data, for NACE H: "Transportation and Storage".

[2] Eurostat National Accounts, 2015 data, for NACE H: "Transportation and Storage"

[3] Christopher M (2016) Logistics and supply chain management, 5th edn. Pearson, Harlow

[4] Dey, A., LaGuardia, P., & Srinivasan, M. (2011). Building sustainability in logistics operations: A research agenda. In Management Research Review. https://doi.org/10.1108/01409171111178774

[5] Jonsson P (2008) Logistics and supply chain management. McGraw-Hill, New York

[6] Montreuil, B. (2011). Toward a Physical Internet: meeting the global logistics sustainability grand challenge. Logistics Research. https://doi.org/10.1007/s12159-011-0045-x

[7] Richards, G. (2014). Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs in the Modern Warehouse. In Journal of Chemical Information and Modeling. https://doi.org/10.1017/CBO9781107415324.004

[8] Palazzi, C. E. (2015). Drone indoor self-localization. DroNet 2015 - Proceedings of the 2015 Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use. https://doi.org/10.1145/2750675.2750677

[9] L. Heuser, Z. Nochta, N.C. Trunk, ICT shaping the world: A scientific view. ETSI, Wiley Publication, London, 2008

[10] Calero Valdez, A., Brauner, P., Schaar, A. K., Holzinger, A., & Ziefle, M. (2015). Reducing Complexity with Simplicity - Usability Methods for Industry 4.0. 19th Triennial Congress of the International Ergonomics Association (IEA 2015). https://doi.org/10.13140/RG.2.1.4253.6809

[11] Akarca, O. (2019, March 4). AN OVERVIEW OF THE HISTORY AND IMPORTANCE OF LOGISTICS. More Than Shipping. https://www.morethanshipping.com/an-overview-of-the- history-and-importance-of-logistics/

[12] Vitasek, K. (2013). Supply chain management: Terms and Glossary. Healthcare Informatics: The Business Magazine for Information and Communication Systems. https://doi.org/10.1201/9781420025705.ch2

[13] Nyhuis, P., & Wiendahl, H. P. (2009). Fundamentals of production logistics: Theory, tools and applications. In Fundamentals of Production Logistics: Theory, Tools and Applications. https://doi.org/10.1007/978-3-540-34211-3

[14] Strandhagen, J. O., Vallandingham, L. R., Fragapane, G., Strandhagen, J. W., Stangeland, A. B. H., & Sharma, N. (2017). Logistics 4.0 and emerging sustainable business models. Advances in Manufacturing. https://doi.org/10.1007/s40436-017-0198-1

[15] Simchi-Levi Kaminsky, P., & Simchi-Levi, E., D. (2008). Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies. 3rd Edition: McGraw-Hill. In Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies. https://doi.org/10.1016/j.dss.2011.10.008

[16] Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. In European Journal of Operational Research. https://doi.org/10.1016/j.ejor.2014.07.012

[17] Setia P, Venkatesh V, Joglekar S (2013) Leveraging digital technologies: how information quality leads to localized capabilities and customer service performance. MIS Q 37(2):565–590

[18] Rushton, A., Croucher, P., & Baker, P. (2006). The handbook of logistics and distribution management. Project Management Journal. https://doi.org/10.1371/journal.pone.0030504

[19] Gu, J., Goetschalckx, M., & McGinnis, L. F. (2007). Research on warehouse operation: A comprehensive review. European Journal of Operational Research. https://doi.org/10.1016/j.ejor.2006.02.025

[20] Companik, E., Gravier, M. J., & Farris, M. T. (2018). Feasibility of warehouse drone adoption and implementation. Journal of Transportation Management. https://doi.org/10.22237/jotm/1541030640

[21] Brynjolfsson, E., Hu, Y. J., & Rahman, M. S. (2013). Competing in the age of omnichannel retailing. MIT Sloan Management Review.

[22] Prajogo, D., & Olhager, J. (2012). Supply chain integration and performance: The effects of long-term relationships, information technology and sharing, and logistics integration. International Journal of Production Economics. https://doi.org/10.1016/j.ijpe.2011.09.001

[23] Bartevyan, L. (2015). Industry 4.0 - Summary report. In DLG-Expert Report.

[24] OECD (2017) The next production revolution: implications for governments and business. OECD Publishing, Paris

[25] Naboni, R., & Paoletti, I. (2015). The third industrial revolution. SpringerBriefs in Applied Sciences and Technology. https://doi.org/10.1007/978-3-319-04423-1_2

[26] Kagermann, H., Wahlster, W., & Helbig, J. (2013). Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group.

[27] Manyika, J., Chui, M., Bisson, P., Woetzel, J., Dobbs, R. Bughin, J., Aharaon, D. 2015. Unlocking the Potential of Internet of Things. McKinsey Global Institute Report. June 2015.

[28] Wallace, E. & Riddick, F. (2013). Panel on Enabling Smart Manufacturing, APMS 2013, State College, USA.

[29] Thoben, K. D., Wiesner, S. A., & Wuest, T. (2017). "Industrie 4.0" and smart manufacturing- a review of research issues and application examples. In International Journal of Automation Technology. https://doi.org/10.20965/ijat.2017.p0004

[30] Berce, P. (2016). The fourth industrial revolution. In Academic Journal of Manufacturing Engineering. https://doi.org/10.4337/9781786430328.00006

[31] Hermann, M., Pentek, T., & Otto, B. (2016). Design principles for industrie 4.0 scenarios. Proceedings of the Annual Hawaii International Conference on System Sciences. https://doi.org/10.1109/HICSS.2016.288

[32] Giusto, D., Iera, A., Morabito, G., & Atzori, L. (2010). The Internet of Things: 20th Tyrrhenian Workshop on Digital Communications. In Vasa. https://doi.org/10.1007/978-1-4419-1674-7

[33] Lee, E. A. (2008). Cyber physical systems: Design challenges. Proceedings - 11th IEEE Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing, ISORC 2008. https://doi.org/10.1109/ISORC.2008.25

Jeschke, S., Brecher, C., Meisen, T., Özdemir, D., & Eschert, T. (2017). Industrial Internet of Things and Cyber Manufacturing Systems. https://doi.org/10.1007/978-3-319-42559-7_1

[34] Lucke, D., Constantinescu, C., & Westkämper, E. (2008). Smart Factory - A Step towards the Next Generation of Manufacturing. In Manufacturing Systems and Technologies for the New Frontier. https://doi.org/10.1007/978-1-84800-267-8_23.

[35] McFarlane, D., Sarma, S., Chirn, J. L., Wong, C. Y., & Ashton, K. (2003). Auto ID systems and intelligent manufacturing control. Engineering Applications of Artificial Intelligence. https://doi.org/10.1016/S0952-1976(03)00077-0

[36] Stock, T., & Seliger, G. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0.

Procedia CIRP. https://doi.org/10.1016/j.procir.2016.01.129

[37] Wang, X., Ong, S. K., & Nee, A. Y. C. (2016). A comprehensive survey of augmented reality assembly research. Advances in Manufacturing. https://doi.org/10.1007/s40436-015-0131-4

[38] McAfee, A., & Brynjolfsson, E. (2012). Big data: The management revolution. Harvard Business Review.

[39] Babich, V., & Hilary, G. (2020). Distributed ledgers and operations: What operations management researchers should know about blockchain technology. Manufacturing and Service Operations Management. https://doi.org/10.1287/MSOM.2018.0752

[40] Gerbert, P., Lorenz, M., Rubmann, M., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. BCG Perspective. https://doi.org/10.1007/978-981-13-3384-2_13

[41] Jiao, J., & Tseng, M. M. (2004). Customizability analysis in design for mass customization. CAD Computer Aided Design. https://doi.org/10.1016/j.cad.2003.09.012

[42] Berman, B. (2012). 3-D printing: The new industrial revolution. Business Horizons. https://doi.org/10.1016/j.bushor.2011.11.003

[43] Miorandi, D., Sicari, S., De Pellegrini, F., & Chlamtac, I. (2012). Internet of things: Vision, applications and research challenges. In Ad Hoc Networks. https://doi.org/10.1016/j.adhoc.2012.02.016

[44] Xu, X. (2012). From cloud computing to cloud manufacturing. Robotics and Computer-Integrated Manufacturing. https://doi.org/10.1016/j.rcim.2011.07.002

[45] Zhang, L., Luo, Y., Tao, F., Li, B. H., Ren, L., Zhang, X., Guo, H., Cheng, Y., Hu, A., & Liu, Y. (2014). Cloud manufacturing: a new manufacturing paradigm. Enterprise Information Systems. https://doi.org/10.1080/17517575.2012.683812

[46] Hassanalian, M., & Abdelkefi, A. (2017). Classifications, applications, and design challenges of drones: A review. In Progress in Aerospace Sciences. https://doi.org/10.1016/j.paerosci.2017.04.003

[47] Premm, M., & Kirn, S. (2015). A multiagent systems perspective on industry 4.0 supply networks. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). https://doi.org/10.1007/978-3-319-27343-3_6

[48] Bo, Y., & Guangwen, H. (2009). Supply chain information transmission based on RFID and internet of things. 2009 Second ISECS International Colloquium on Computing, Communication, Control, and Management, CCCM 2009. https://doi.org/10.1109/CCCM.2009.5267755

[49] Prinz, C., Morlock, F., Freith, S., Kreggenfeld, N., Kreimeier, D., & Kuhlenkötter, B. (2016). Learning Factory Modules for Smart Factories in Industrie 4.0. Procedia CIRP. https://doi.org/10.1016/j.procir.2016.05.105

[50] Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. Procedia Manufacturing. https://doi.org/10.1016/j.promfg.2017.09.045

[51] Macaulay, J., Buckalew, L., & Chung, G. (2015). Internet of Things in Logistics. DHL Trend Research.

[52] Watts, A. C., Perry, J. H., Smith, S. E., Burgess, M. A., Wilkinson, B. E., Szantoi, Z., Ifju, P. G., & Percival, H. F. (2010). Small Unmanned Aircraft Systems for Low-Altitude Aerial Surveys. Journal of Wildlife Management. https://doi.org/10.2193/2009-425

[53] Cai, G., Dias, J., & Seneviratne, L. (2014). A Survey of Small-Scale Unmanned Aerial Vehicles: Recent Advances and Future Development Trends. In Unmanned Systems. https://doi.org/10.1142/S2301385014300017

[54] Hassanalian, M., & Abdelkefi, A. (2017). Design, manufacturing, and flight testing of a fixed wing micro air vehicle with Zimmerman planform. Meccanica. https://doi.org/10.1007/s11012- 016-0475-2

[55] Chapman, A. (2016, June 3). Types of Drones: Multi-Rotor vs Fixed-Wing vs Single Rotor vs Hybrid VTOL. Australia UAV. https://www.auav.com.au/articles/drone-types/

[56] Wawrla, L., Maghazei, O., & Netland, P. D. T. (2019). Applications of drones in warehouse operations, Whitepaper. August, 0–13.

[57] Gheorghe Amza, C., & Cantemir, D. (2018). “Guidelines on Industry 4.0 and Drone Entrepreneurship for VET students.” www.danmar-computers.com.pl

[58] Fernández-Caramés, T. M., Blanco-Novoa, O., Froiz-Míguez, I., & Fraga-Lamas, P. (2019). Towards an Autonomous Industry 4.0 Warehouse: A UAV and Blockchain-Based System for Inventory and Traceability Applications in Big Data-Driven Supply Chain Management. Sensors (Basel, Switzerland), 19(10). https://doi.org/10.3390/s19102394

[59] Gharibi, M., Boutaba, R., & Waslander, S. L. (2016). Internet of Drones. IEEE Access, 4, 1148–1162. https://doi.org/10.1109/ACCESS.2016.2537208

[60] D. Gross. (2013). Amazon’s Drone Delivery: How Would it Work? [Online]. Available: http://www.cnn.com/2013/12/02/tech/

[61] FedEx Corporation. (2015). Q1 Fiscal 2015 Statistics. [Online]. Available: http://investors.fedex.com/files/doc_downloads/statistical/ FedEx-Q1-FY15-Stat-Book_v001_t195uu.pdf.

[62] Global Trade Item Number Official Web Page at GS1 Website. https://www.gs1.org/gtin

[63] Finkenzeller, K. (2010). RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and near-Field Communication. In RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and near-Field Communication. https://doi.org/10.1002/9780470665121

[64] Fraga-Lamas, P., Noceda-Davila, D., Fernández-Caramés, T. M., Díaz-Bouza, M. A., & Vilar-Montesinos, M. (2016). Smart pipe system for a shipyard 4.0. Sensors (Switzerland). https://doi.org/10.3390/s1612218

[65] Ganesan, R., Krumm, J., Pankalla, S., Ludwig, K., & Glesner, M. (2013). Design of an organic electronic label on a flexible substrate for temperature sensing. European Solid-State Circuits Conference. https://doi.org/10.1109/ESSCIRC.2013.6649163

[66] Todd, B., Phillips, M., Schultz, S. M., Hawkins, A. R., & Jensen, B. D. (2008). RFID threshold accelerometer. AUTOTESTCON (Proceedings). https://doi.org/10.1109/AUTEST.2008.4662584

[67] Amin, E. M., Bhuiyan, M. S., Karmakar, N. C., & Winther-Jensen, B. (2014). Development of a low cost printable chipless RFID humidity sensor. IEEE Sensors Journal. https://doi.org/10.1109/JSEN.2013.2278560

[68] Fernandez-Carames, T. M., & Fraga-Lamas, P. (2018). A Review on Human-Centered IoT-Connected Smart Labels for the Industry 4.0. IEEE Access. https://doi.org/10.1109/ACCESS.2018.2833501

[69] Fraga-Lamas, P., Fernandez-Carames, T. M., Noceda-Davila, D., Diaz-Bouza, M. A., Vilar-Montesinos, M., Pena-Agras, J. D., & Castedo, L. (2017). Enabling automatic event detection for the pipe workshop of the shipyard 4.0. 2017 56th FITCE Congress, FITCE 2017. https://doi.org/10.1109/FITCE.2017.8093002

[70] ProVIEW Smart Label Official Web Page. https://www.omni-id.com/rfid-in-manufacturing/ (accessed

[71] Fraga-Lamas, P., Fernández-Caramés, T. M., & Castedo, L. (2017). Towards the internet of smart trains: A review on industrial IoT-connected railways. Sensors (Switzerland). https://doi.org/10.3390/s17061457

[72] Hernández-Rojas, D. L., Fernández-Caramés, T. M., Fraga-Lamas, P., & Escudero, C. J. (2018). Design and practical evaluation of a family of lightweight protocols for heterogeneous sensing through BLE beacons in IoT telemetry applications. Sensors (Switzerland). https://doi.org/10.3390/s18010057

[73] Fernández-Caramés, T. M., González-López, M., & Castedo, L. (2010). FPGA-based vehicular channel emulator for real-time performance evaluation of IEEE 802.11p transceivers. Eurasip Journal on Wireless Communications and Networking. https://doi.org/10.1155/2010/607467

[74] ZigBee Alliance. http://www.zigbee.org

[75] Kim, A. N., Hekland, F., Petersen, S., & Doyle, P. (2008). When HART goes wireless: Understanding and implementing the WirelessHART standard. IEEE International Conference on Emerging Technologies and Factory Automation, ETFA. https://doi.org/10.1109/ETFA.2008.4638503

[76] Zhong, R. Y., Xu, C., Chen, C., & Huang, G. Q. (2017). Big Data Analytics for Physical Internet-based intelligent manufacturing shop floors. International Journal of Production Research. https://doi.org/10.1080/00207543.2015.1086037

[77] “Leica Aibot”. https://leica-geosystems.com/de-ch/products/uav-systems/copter

[78] “Vtrus launches drones to inspect and protect your warehouses and factories.”. https://techcrunch.com/2018/09/06/vtrus-launches-drones-to-inspect-and-protect-your-warehouses-and-factories/.

[79] “PINC Drones”. https://www.pinc.com/

[80] “Doks. Innovation”. https://www.doks-innovation.com/

[81] Inventory-taking drone.”. https://eyesee-drone.com/drone-inventoriste-hardis- group-lance- la-phase-de-test-dun-prototype-en-conditions-reelles/?lang=en.

[82] “Warehouse inventory using dronese.”. https://geodis.com/de- en/newsroom/press-releases/warehouse-invenotry-using-drones-geodis-and-delta-drone-have- entered-the-industrialization-production-phas-of-their-completely-automated-solution?forced=de-en

[83] “Infinium Scan.”/www.infiniumrobotics.com/infinium-scan/.

[84] Chen, Albert & Fu, Xin. (2017). Data + Intuition: A Hybrid Approach to Developing Product North Star Metrics. 617-625. 10.1145/3041021.3054199.

[85] Miklos A. Vasarhelyi (2013) Formalization of Standards, Automation, Robots, and IT Governance. Journal of Information Systems: Spring 2013, Vol. 27, No. 1, pp. 1-11.

[86] Issa, Hussein & Sun, Ting & Vasarhelyi, Miklos. (2016). Research Ideas for Artificial Intelligence in Auditing: The Formalization of Audit and Workforce Supplementation. Journal of Emerging Technologies in Accounting. 13. 1-20. 10.2308/jeta-10511.

[87] Muller, M. (2011) Essentials of Inventory Management, 2nd Edition, American Management Association

[88] Bacharel, G., & Ferraz, I. (2020). Drones for Intralogistics using IoT Dissertation in Telecommunications and Informatics Engineering. December; thesis submitted for evaluation on 2020.

[89] Barnes, C. R., 2002. Developing an Effective Business Case for a Warehouse Management System, Nova Iorque: Alexander Communications Group, Inc.

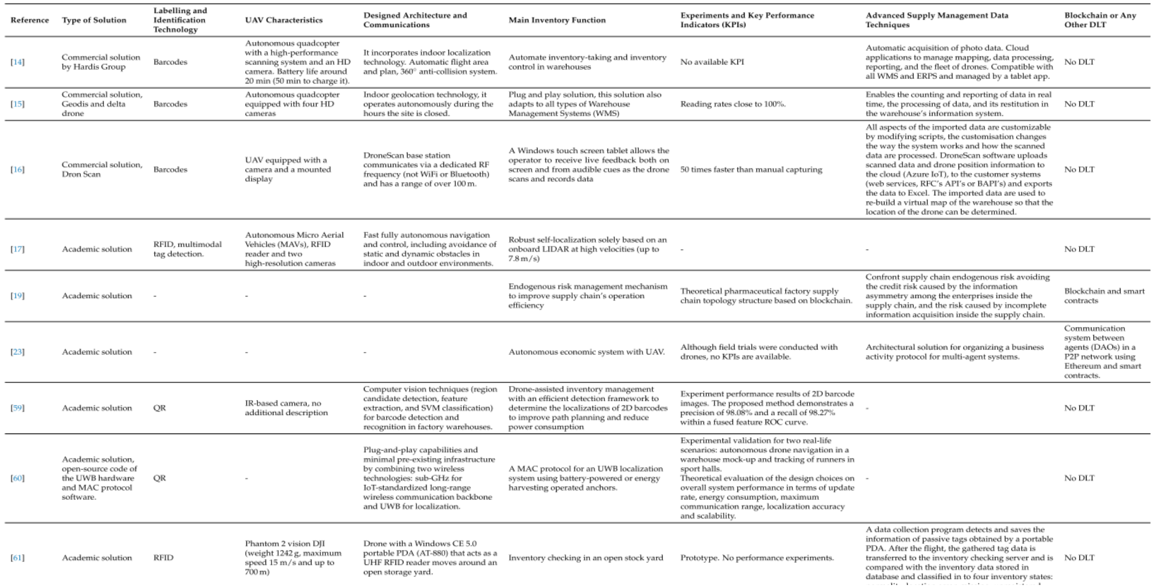
[90] Hill, J. M., 2002. Justifying Warehouse Management Systems, Toledo: ESYNC.

Attachments

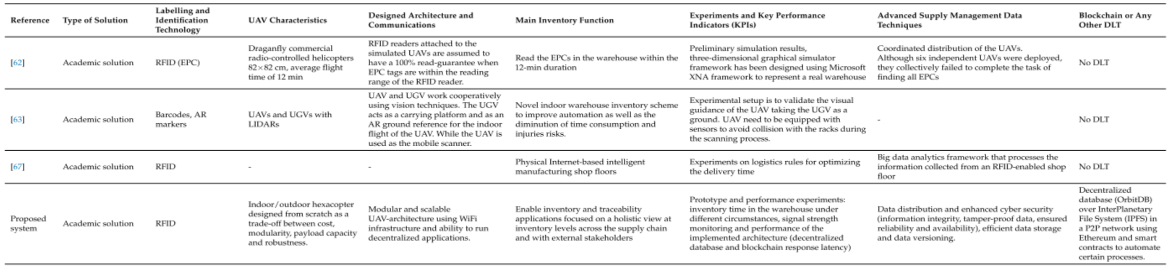
Attachment 1- Main characteristics of the most relevant communications and identification technologies for inventory and traceability applications (adapted from [59])

Technology	Frequency Band	Max. Range in Optimal Conditions	Data Rate	Power Type	Main Features	Main Limitations for Inventory Applications	Popular Applications
ANT+	2.4Ghaz	30m	20kbit/s	Ultra-low power	Up to 65,533 nodes	Lack of commercial inventory tags	Health, sport monitoring
Barcode/QR	-	<4m	-	No power	Very low cost, visual decoding	Need for LOS	Asset tracking and marketing
Bluetooth 5 LE	2.4 GHz	<400m	1360 kbit/s	Low power	Batteries only last days to weeks	Batteries need to be recharged, shared communications radio frequency	Beacons, wireless headsets
DASH7/ISO 18000-7	315-915 MHZ	<10km	27,8 kbit/s	Very low power, alkaline batteries last months to years	Long reading distance, multi-year battery	Batteries need to be recharged, shared communications radio frequency	Smart industry and military
HF RFID	**3-30 MHz**	**A few meters**	**<640 kbit/s**	**No power**	**NLOS, no need for batteries**	**Relatively short reading range**	**Smart Industry, payments, asset tracking**
Infrared (IrDA)	300 GHz to 430 THz	A few meters	2.4 kbit/s – 1 Gbit/s	Low power	Low-cost hardware, security, high speed	Need for LOS, batteries may drain fast when transmitting continuously	Remote control, data transfer
IQRF	433 MHz,868 MHz or 916 MHz	Hundreds of meters	19.2 kbit/s	Low power	Long communications range	Shared communications radio frequency NLOS,	Internet of Things and M2M applications
LF RFID	**30-300 KHz**	**<10 cm**	**<640 kbit/s**	**No power**	**NLOS, low cost**	**Very short reading distance (in general, a few centimetres) Dependent**	**Smart Industry and security access**
NB-IoT	LTE in-band, guard-band 13,56 MHz	<35 km	<250 kbit/s	Low power	Long reading range	Dependent on third-party infrastructure	IoT applications
NFC	13,56 MHZ	<20 cm	424 kbit/s	No power	Low cost	Short reading distance	Ticketing and payments
ZigBee (infrared communications)	868-915 MHz, 2.4 GHz	<100m	20-250 kbit/s	Very low power (batteries last months to years	Easy to scale, up to 65,536 nodes	Relatively expensive hardware, potential interference from devices in the same frequency band	Smart Home and industrial applications
WirelessHART (UWB)	2.4 GHz	<10m	250 kbit/s	Low power (Batteries last several years)	Compatibility with HART protocol, standardized as IEC 62591	Shared communications radio frequency, lack of commercial inventory tags	Wireless sensor network applications
UHF RFID	30 MHz-4 GHz	Tens of meters	<640 kbit/s	Very low power or no power	NLOS, wide range of suppliers, low cost	Propagation problems with metal and liquids (specially with high transmission frequencies)	Smart Industry, asset tracking and toll payment
UWB/IEEE 802.15.3a	3.1 to 10.6 GHz	<10m	>110 Mbit/s	Low power (batteries last hours to days)	Accurute positioning (centimetre accuracy)	Expensive hardware, propagation problems in metallic environments High	Real Time Location Systems (RTLS), short-distance streaming
Wi-Fi (IEEE 802.11b/g/n/ac)	2.4-5 GHz	<150m	Up to 433 Mbit/s (one stream)	High power (bateeires may last hours)	High speed, ubiquity	Short battery life	Internet access, broadband

Attachment 2- Comparison of the main features of the most relevant UAB-based inventory systems (adapted from [59])

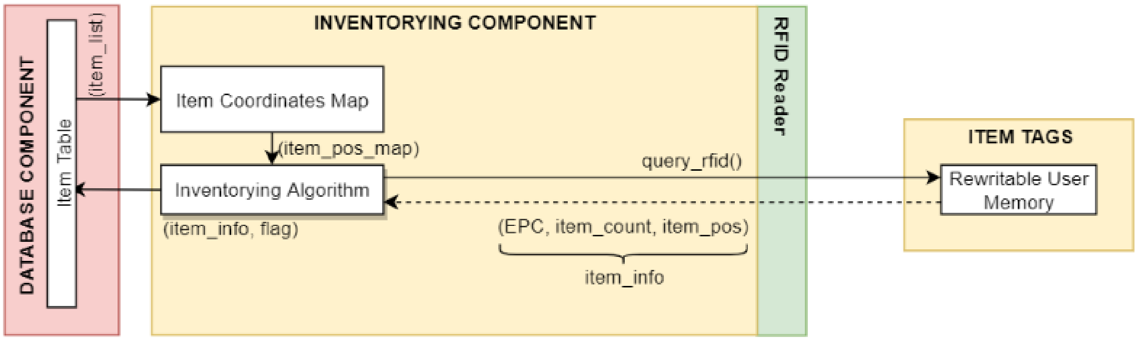


Reference	Type of Solution	Labelling and Identification Technology	UAV Characteristics	Designed Architecture and Communications	Main Inventory Function	Experiments and Key Performance Indicators (KPIs)	Advanced Supply Management Data Techniques	Blockchain or Any Other DLT
[14]	Commercial solution by Hardis Group	Barcodes	Autonomous quadcopter with a high-performance scanning system and an HD camera. Battery life around 20 min (50 min to charge it).	It incorporates indoor localization technology. Automatic flight area and plan, 360° anti-collision system.	Automate inventory-taking and inventory control in warehouses	No available KPI	Automatic acquisition of photo data. Cloud applications to manage mapping, data processing, reporting, and the fleet of drones. Compatible with all WMS and ERPS and managed by a tablet app.	No DLT
[15]	Commercial solution, Geodis and delta drone	Barcodes	Autonomous quadcopter equipped with four HD cameras	Indoor geolocation technology, it operates autonomously during the hours the site is closed.	Plug and play solution, this solution also adapts to all types of Warehouse Management Systems (WMS)	Reading rates close to 100%.	Enables the counting and reporting of data in real time, the processing of data, and its restitution in the warehouse's information system.	No DLT
[16]	Commercial solution, Dron Scan	Barcodes	UAV equipped with a camera and a mounted display	DroneScan base station communicates via a dedicated RF frequency (not WiFi or Bluetooth) and has a range of over 100 m.	A Windows touch screen tablet allows the operator to receive live feedback both on screen and from audible cues as the drone scans and records data	50 times faster than manual capturing	All aspects of the imported data are customizable by modifying scripts, the customisation changes the way the system works and how the scanned data are processed. DroneScan software uploads scanned data and drone position information to the cloud (Azure IoT), to the customer systems (web services, RFC's API's or BAPI's) and exports the data to Excel. The imported data are used to re-build a virtual map of the warehouse so that the location of the drone can be determined.	No DLT
[17]	Academic solution	RFID, multimodal tag detection.	Autonomous Micro Aerial Vehicles (MAVs), RFID reader and two high-resolution cameras	Fast fully autonomous navigation and control, including avoidance of static and dynamic obstacles in indoor and outdoor environments.	Robust self-localization solely based on an onboard LIDAR at high velocities (up to 7.8 m/s)	-	-	No DLT
[19]	Academic solution	-	-	-	Endogenous risk management mechanism to improve supply chain's operation efficiency	Theoretical pharmaceutical factory supply chain topology structure based on blockchain.	Confront supply chain endogenous risk avoiding the credit risk caused by the information asymmetry among the enterprises inside the supply chain, and the risk caused by incomplete information acquisition inside the supply chain.	Blockchain and smart contracts
[23]	Academic solution	-	-	-	Autonomous economic system with UAV.	Although field trials were conducted with drones, no KPIs are available.	Architectural solution for organizing a business activity protocol for multi-agent systems.	Communication system between agents (DAOs) in a P2P network using Ethereum and smart contracts.
[59]	Academic solution	QR	IR-based camera, no additional description	Computer vision techniques (region candidate detection, feature extraction, and SVM classification) for barcode detection and recognition in factory warehouses.	Drone-assisted inventory management with an efficient detection framework to determine the localizations of 2D barcodes to improve path planning and reduce power consumption	Experiment performance results of 2D barcode images. The proposed method demonstrates a precision of 98.08% and a recall of 98.27% within a fused feature ROC curve.	-	No DLT
[60]	Academic solution, open-source code of the UWB hardware and MAC protocol software.	QR	-	Plug-and-play capabilities and minimal pre-existing infrastructure by combining two wireless technologies: sub-GHz for IoT-standardized long-range wireless communication backbone and UWB for localization.	A MAC protocol for an UWB localization system using battery-powered or energy harvesting operated anchors.	Experimental validation for two real-life scenarios: autonomous drone navigation in a warehouse mock-up and tracking of runners in sport halls. Theoretical evaluation of the design choices on overall system performance in terms of update rate, energy consumption, maximum communication range, localization accuracy and scalability.	-	No DLT
[61]	Academic solution	RFID	Phantom 2 vision DJI (weight 1242 g, maximum speed 15 m/s and up to 700 m)	Drone with a Windows CE 5.0 portable PDA (AT-880) that acts as a UHF RFID reader moves around an open storage yard.	Inventory checking in an open stock yard	Prototype. No performance experiments.	A data collection program detects and saves the information of passive tags obtained by a portable PDA. After the flight, the gathered tag data is transferred to the inventory checking server and is compared with the inventory data stored in database and classified in to four inventory states:	No DLT

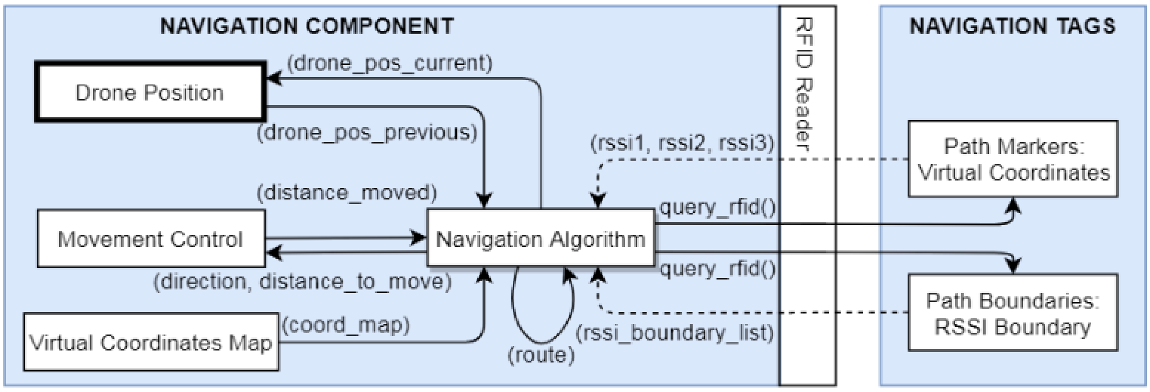


Reference	Type of Solution	Labelling and Identification Technology	UAV Characteristics	Designed Architecture and Communications	Main Inventory Function	Experiments and Key Performance Indicators (KPIs)	Advanced Supply Management Data Techniques	Blockchain or Any Other DLT
[62]	Academic solution	RFID (EPC)	Draganfly commercial radio-controlled helicopters 82×82 cm, average flight time of 12 min	RFID readers attached to the simulated UAVs are assumed to have a 100% read-guarantee when EPC tags are within the reading range of the RFID reader.	Read the EPCs in the warehouse within the 12-min duration	Preliminary simulation results, three-dimensional graphical simulator framework has been designed using Microsoft XNA framework to represent a real warehouse	Coordinated distribution of the UAVs. Although six independent UAVs were deployed, they collectively failed to complete the task of finding all EPCs	No DLT
[63]	Academic solution	Barcodes, AR markers	UAVs and UGVs with LIDARs	UAV and UGV work cooperatively using vision techniques. The UGV acts as a carrying platform and as an AR ground reference for the indoor flight of the UAV. While the UAV is used as the mobile scanner.	Novel indoor warehouse inventory scheme to improve automation as well as the diminution of time consumption and injuries risks.	Experimental setup is to validate the visual guidance of the UAV taking the UGV as a ground. UAV need to be equipped with sensors to avoid collision with the racks during the scanning process.	-	No DLT
[67]	Academic solution	RFID	-	-	Physical Internet-based intelligent manufacturing shop floors	Experiments on logistics rules for optimizing the delivery time	Big data analytics framework that processes the information collected from an RFID-enabled shop floor	No DLT
Proposed system	Academic solution	RFID	Indoor/outdoor hexacopter designed from scratch as a trade-off between cost, modularity, payload capacity and robustness.	Modular and scalable UAV-architecture using WiFi infrastructure and ability to run decentralized applications.	Enable inventory and traceability applications focused on a holistic view at inventory levels across the supply chain and with external stakeholders	Prototype and performance experiments: inventory time in the warehouse under different circumstances, signal strength monitoring and performance of the implemented architecture (decentralized database and blockchain response latency)	Data distribution and enhanced cyber security (information integrity, tamper-proof data, ensured reliability and availability), efficient data storage and data versioning.	Decentralized database (OrbitDB) over InterPlanetary File System (IPFS) in a P2P network using Ethereum and smart contracts to automate certain processes.

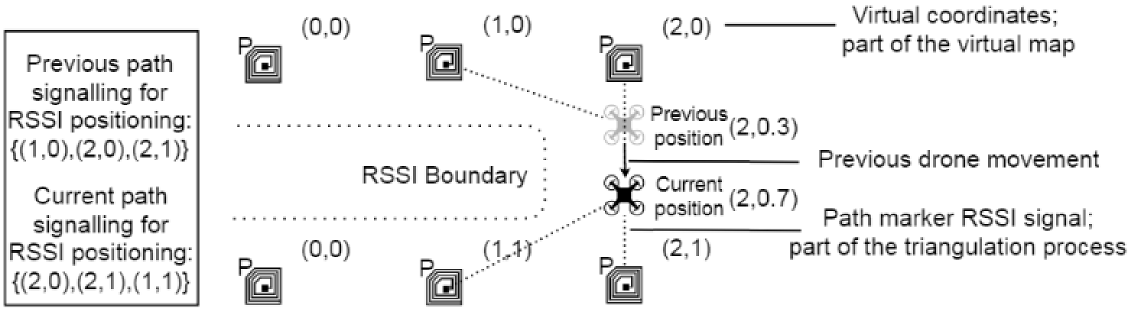
Attachment 3- Software architecture of the inventory component



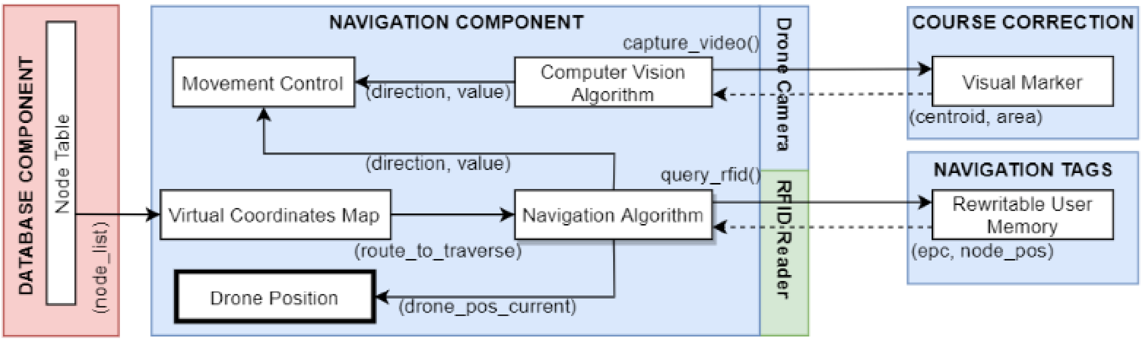
Attachment 4- RSSI Triangulation approach to the software architecture of the navigation component



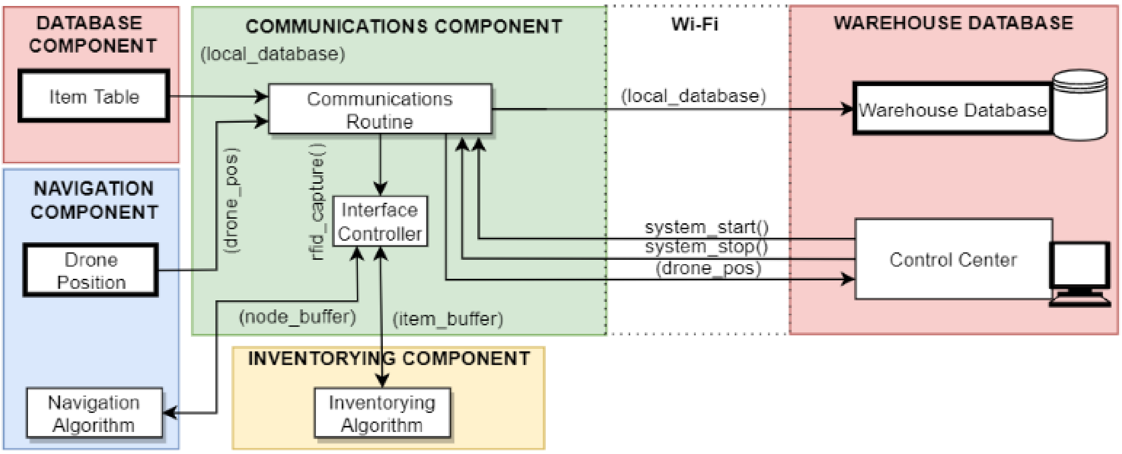
Attachment 5- Top-down view of the drone navigation solution in an example configuration.



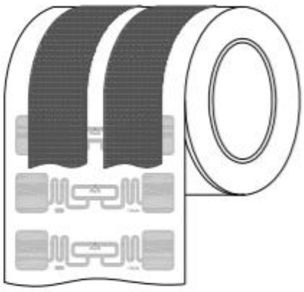
Attachment 6 – Course Correction approach to the software architecture of the navigation component.



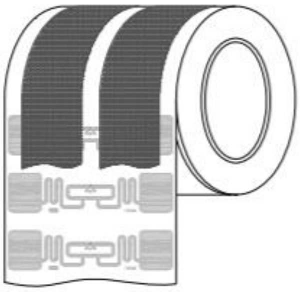
Attachment 7 – Software architecture of the communications component



Attachment 8 – ALN-9662 Inlay Orientation, Specification, General Dimensions and Stack up

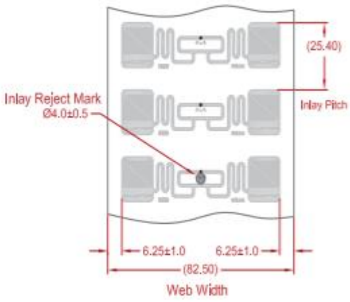


ALN-9662-FRA
(Dry Unslit Roll)

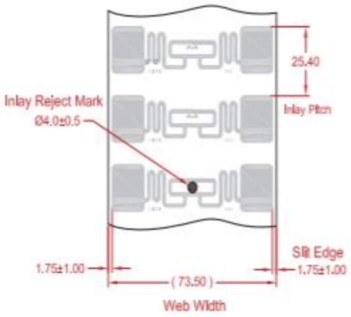


ALN-9662-FSRA
(Dry Slit Roll)

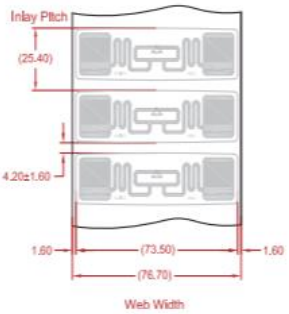
ALN-9662-FWRCA / FWRWA
(Clear / White Wet Inlay)



ALN-9662-FRA
(Dry Unslit Roll)

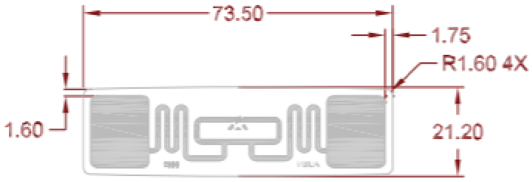


ALN-9662-FSRA
(Dry Slit Roll)



ALN-9662-FWRCA / FWRWA
(Clear / White Wet Inlay)

ALN-9662-FRA / FSRA
(Dry Unslit / Slit Inlay)



ALN-9662-FWRCA / FWRWA
(Clear / White Wet Inlay)

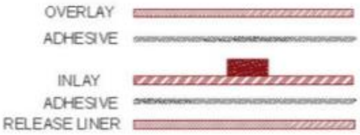
DRY INLAY THICKNESS, ±10%	
OVER ANTENNA	0.05 mm
OVER CHIP	0.25 mm

CLEAR WET INLAY THICKNESS, ±10%	
OVER ANTENNA	0.08 mm
OVER CHIP	0.28 mm

WHITE WET INLAY THICKNESS, ±10%	
OVER ANTENNA	0.16 mm
OVER CHIP	0.36 mm

ALN-9662-FRA / FSRA
(Dry Unslit / Slit Inlay)

ALN-9662-FWRCA
(Clear Wet Inlay)



ALN-9662-FWRWA
(White Wet Inlay)

Attachment 9 – Video feedback processed through OpenCV. Featured in the top-left are the movement cues for the centroid reach the center of the video feedback. The vector norm from the center of the screen to the centroid is pictured in the middle of the screen. Below it is the computed area of the shape defined by the green bounding rectangle

```
MOVE:
BACK
LEFT

RTT
```

```
232.7767170487633
71794.5
```

Attachment 10 – Forklift Trucks - Cost Comparison: Barcode Scanning Technology & Work Platforms to Elevate Personnel

Motorola MC9190-G

- Windows Mobile 6.3
- 43 key keyboard
- Wi-Fi, Bluetooth
- 3.7" VGA Color Touchscreen
- Laser scanner
- Cost: $2,509.10 via BarcodesInc

Wasp WLR8950

- Connects to PC with USB cable
- Scans 1D, colored barcodes up to 12”
- 230-450 scans per second decode rate
- Bi-color LED technology
- Cost: $149.00. via Wasp Barcode

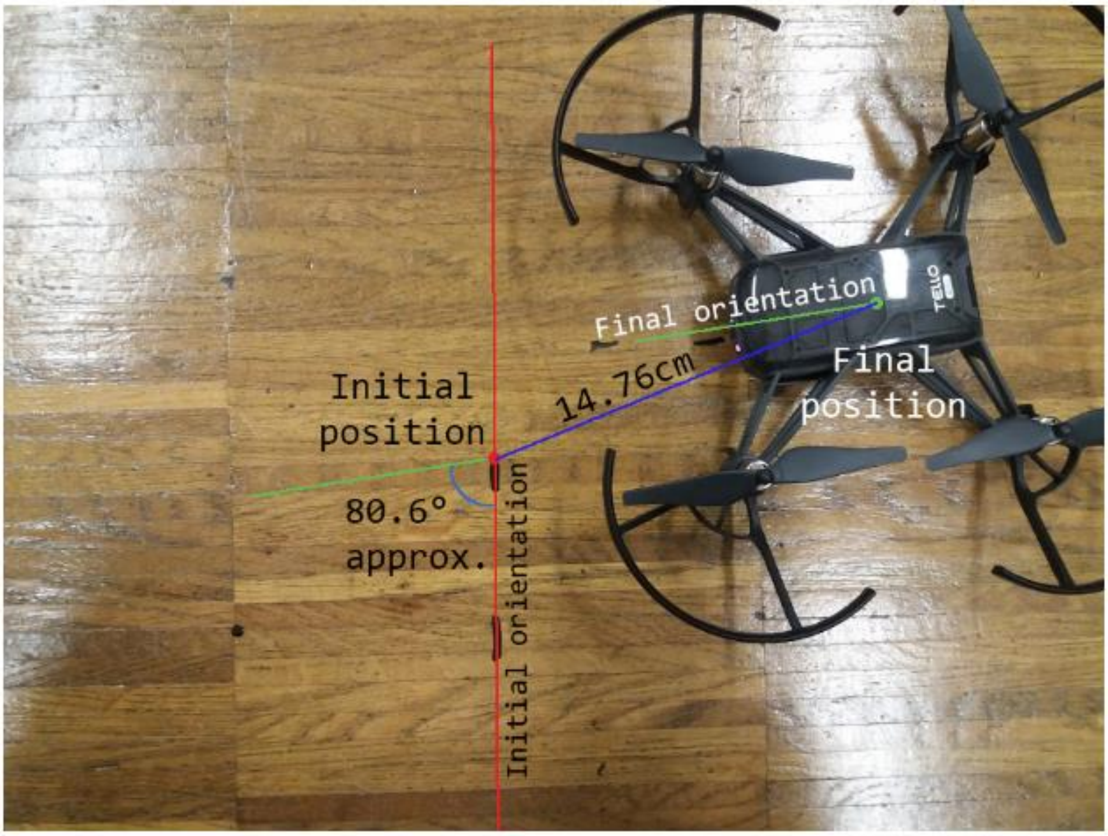
Fleetio Parts

- View location-based database of parts
- Update part quantities dynamically
- Scan and recognize part UPC & QR codes
- Cost: Free for Fleetio users

A forklift work platform is a unit or cage that is integrated (built in), or designed to be supported on the forks of a lift truck.

Work platforms that are used to elevate (lift or raise) workers must provide appropriate support and safety measures. Generally speaking, these platforms are either commercially manufactured, or designed and certified by a professional engineer for this specific purpose.

Attachment 11 – Comparison between drone takeoff position and orientation and landing position and orientation & Solution [89]



After several tests with the drone in a stationary hover, it was determined that the drone yawed clockwise on average 0.21o/s. This rate of involuntary yawing is not high enough to cause an update to the IMU's attitude values. Since rotation commands were already used, the simplest fix was to code a small threaded cycle to take into account the number of seconds passed since takeoff, and whenever the drone reached the end of an aisle, perform a second yaw correction. This correction would rotate the drone counterclockwise according to the following formula, where TURN_FIX is the angle to rotate counterclockwise, and t is the number of seconds that have passed since takeoff or since the last correction:

TURN_FIX = 0.21t

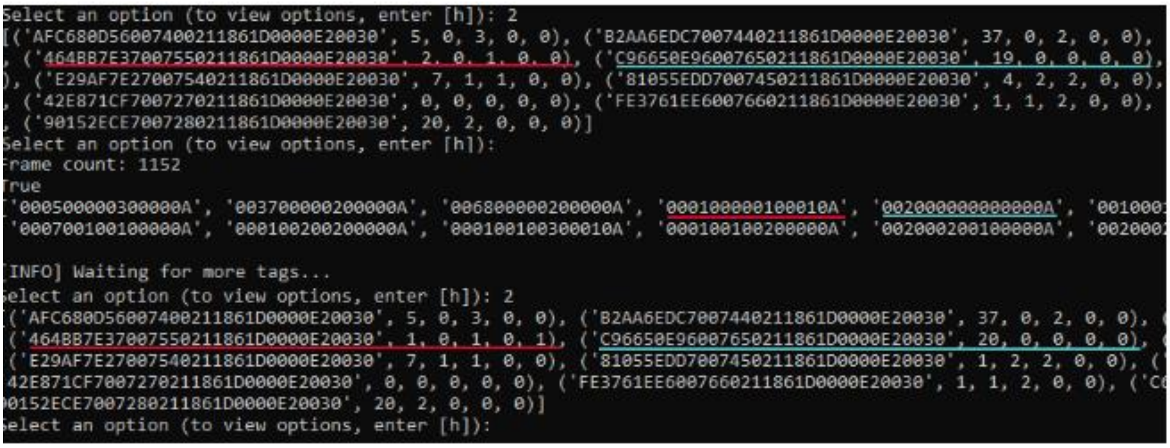
After correcting the drone's yaw, TURN FIX is added to the OFFSET variable according to the following expression:

OFFSET_NEW = OFFSET_OLD +TURN_FIX

This expression is required because even though the drone would be rotating to its ideal attitude, the

IMU did not account for its involuntary yawing. Yet, the positioning correction command is issued and has an impact on the yaw value registered by the IMU since it accounts of a counterclockwise rotation of several degrees. Consequently, the OFFSET variable is combined with the drone's current heading before determining the yaw correction required. This ensures the software stores the correct yaw values for the drone's skewed attitude values.

Attachment 12 – Local database populated with 13 items



```
Select an option (to view options, enter [h]): 2
[('AFC680D56007400211861D0000E20030', 5, 0, 3, 0, 0), ('B2AA6EDC7007440211861D0000E20030', 37, 0, 2, 0, 0),
, ('464BB7E37007550211861D0000E20030', 2, 0, 1, 0, 0), ('C96650E96007650211861D0000E20030', 19, 0, 0, 0, 0),
), ('E29AF7E27007540211861D0000E20030', 7, 1, 1, 0, 0), ('81055EDD7007450211861D0000E20030', 4, 2, 2, 0, 0),
, ('42E871CF7007270211861D0000E20030', 0, 0, 0, 0, 0), ('FE3761EE6007660211861D0000E20030', 1, 1, 2, 0, 0),
, ('90152ECE7007280211861D0000E20030', 20, 2, 0, 0, 0)]
Select an option (to view options, enter [h]):
Frame count: 1152
True
['000500000300000A', '003700000200000A', '006800000200000A', '000100000100010A', '002000000000000A', '001000
 '000700100100000A', '000100200200000A', '000100100300010A', '000100100200000A', '002000200100000A', '002000

[INFO] Waiting for more tags...
Select an option (to view options, enter [h]): 2
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 ('E29AF7E27007540211861D0000E20030', 7, 1, 1, 0, 0), ('81055EDD7007450211861D0000E20030', 1, 2, 2, 0, 0), ('
 42E871CF7007270211861D0000E20030', 0, 0, 0, 0, 0), ('FE3761EE6007660211861D0000E20030', 1, 1, 2, 0, 0), ('C
0152ECE7007280211861D0000E20030', 20, 2, 0, 0, 0)]
Select an option (to view options, enter [h]):
```

The above figure represents the output excerpt of the local database before and after field testing the inventory system. The example follows: In red, an item storage unit had 1 item removed from it and has been marked as misplaced by an on-site employee. Once the tag is scanned, the item count is updated on the local database and the item is marked as misplaced. In cyan, an item storage unit was restocked by 1 unit. Another experiment is seen bellow. The item storage unit, marked as correctly stored in the local database and on the item tag, is scanned. The position advertised by the item tag differs from the one stored in the records. The item's record is updated. This includes the item storage unit's current position and a flag to indicate the item's misplacement. The image bellow represent the output excerpt of flagging a previously unflagged tag due to conflicting item position attributes

```
Select an option (to view options, enter [h]): 2
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 ('E29AF7E27007540211861D0000E20030', 7, 1, 1, 0, 0), ('81055EDD7007450211861D0000E20030', 1, 2, 2, 0, 0), ('89
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[INFO] Item already in DB, updating its record.
[('B23684B66007080211861D0000E20034', 1234, 99, 99, 99, 1)]
True
['123409909909900A']
Select an option (to view options, enter [h]): 2
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Select an option (to view options, enter [h]):
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