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Development of an Intelligent Mobile Robot Prototype for Indoor Material Transportation

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ABSTRACT
This article is focused on methods, techniques and tools to assist the development of products and robots that need to work with precision in indoor environments, besides presenting the main technologies related to the subject, with their respective advantages, disadvantages, challenges. Finally, a prototype of a mobile robot will be proposed and developed. Self-driving vehicles have become part of Industry 4.0. The Fourth Revolution is present in all stages of manufacturing a product, with benefits for safety, profitability, quality, assembly and worker well-being. Intelligent mobile robots have the ability to move in predetermined places, autonomously and without running the risk of colliding with other robots or people, being able to reprogram their trajectories, no longer having the need to place markers when along its route. They are able to carry heavy loads, carry out unhealthy tasks and work 24 hours a day, 7 days a week.

Keywords-Control and Automation Engineering, Mobile Robotics, Smart Robots, Beacons, Mobile autonomous robots.

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I. INTRODUCTION

The development of an intelligent autonomous mobile robot (AMR) for the plant will save time in internal transports and also manage the supply of the lines as well as the delivery time. This mobile technology is innovative when applied to Logistics 4.0. After all, as industrial technologies advance, logistics processes must keep up with these changes. Logistics 4.0 means taking advantage of Industry 4.0 technologies to make logistics processes more efficient, agile, and profitable. It aims to optimize the distribution chain, automate logistics processes, eliminate waste, gain time and reduce costs [1]. Logistics 4.0 is based on investment in technology to improve, mainly, inventory control, line supply and analysis of these processes[2].

Autonomous robots are examples of a technological resource to be applied logistics 4.0. They are programmed by computer systems that indicate the necessary movements according to the factory map. The software developed for the robots also coordinates the tasks to be performed. By inserting labels in batches of goods that activate sensors capable of automatically writing off when items enter stock or leave stock, they can improve the handling of production items. The labels are intended to notify when products are taken to the production line. In this way, it is possible to know what stage each shipment is at, when it was shipped, and when it was delivered to its destination.

After selecting the materials from the stock, the operator will place the items on the vehicle, which transports them to the assembly line. These robots can work side by side with humans, and do not need any isolation, or any tracks or magnetic tapes laid out on the floor in the factory that need constant maintenance. The robots are fully autonomous and plot the best route to the destination point, avoiding obstacles and people. In addition, they do their own battery management and move to the charging station automatically whenever necessary.

Industry 4.0 is being responsible for transforming the entire production chain, the use of robots has brought several benefits. Robots are recommended for performing standardized tasks that depend on a limited number of variables, and are suitable for performing the fulfillment of massive demands [3].

The use of robots in industries brings as a result the reduction of failures and the processing time of production activities, generating cost savings. Robotics innovations have quick installation and great flexibility to change functions or adjust the amount of operators [4].

Robots can be used in unhealthy and hazardous activities, which allows employees to coordinate tasks from a safe location without taking health risks. In addition, by performing the mechanical and repetitive tasks, they allow employees to focus human service on more complicated issues that require more insight, performing more complex activities than those that now make up the majority of their demands [5].

Collaborative type robots, known as COBOTS, are designed and developed to work collaboratively with people and take care of heavy and/or repetitive activities, while people engage in motor and detailed activities that require attention and insight. In addition to this, they can be programmed for complex and dangerous activities, creating a true hybrid team concept [6].

The use of robots within industry brings great advantages in increasing production, product quality, and economic return. Thus, it is important that companies prepare to make their transition to Industry 4.0 in order to remain competitive against the market [7].

Robotics comes to facilitate the execution of mechanical and dangerous tasks, which means that there will be a need to empower employees with the development of more refined skills, allowing it to be able to perform more complex activities. It is important to note that the proposal of Industry 4.0 is not to replace human labor, but rather to make it more efficient and effective [8].

Industry 4.0 also called the Fourth Industrial Revolution, encompasses a broad system of advanced technologies such as artificial intelligence, robotics, internet of things and cloud computing that are changing the ways of production and business models in Brazil and worldwide [9].

Industry 4.0 has also been baptized as the 4th Industrial Revolution, this phenomenon is changing, on a large scale, automation and data exchange, as well as production stages and business models, through the use of machines and computers. Innovation, efficiency and customization are the keywords to define the concept of Industry 4.0 [10].

Industry 4.0 has a significant impact on industry productivity, as it increases the efficiency of resource use and in the development of large-scale products, in addition to providing the integration of Brazil in global value chains [11].

In addition, it will imply transformations in business management, mainly in two aspects: The first is related to the strategy to implement technologies, such as cooperation between information technology (IT) and production areas.

Industry 4.0 is a concept that represents industrial automation and the integration of different technologies such as: Artificial Intelligence, Cloud Computing, Big data, Cyber security, Internet of things, Advanced Robotics, Digital manufacturing, Additive manufacturing, Systems integration and simulation systems with the goal of promoting the digitalization of industrial activities improving processes and increasing productivity [12].

The incorporation of Advanced Robotics, Machine-Machine Connection Systems, the Internet of Things, and the Sensors and Actuators used in this equipment enables machines to "talk" throughout industrial operations. This can enable the generation of information and the connection of the various stages of the value chain, from new product development, design, production, to after-sales [13].

The development of Industry 4.0 in Brazil involves challenges that range from investments in equipment with new technologies, to the adaptation of layouts, adaptation of processes and the forms of relationship between companies along the production chain, creation of new specialties, and development of human resources, among others [14].

Self-guided vehicles have become part of Industry 4.0. The Fourth Revolution is present in all stages of manufacturing a product, with benefits for safety, profitability, quality verification, assembly, and worker well-being. And AGVs are key pieces in this process [15]. From the English term, Automatic Guided Vehicle, AGVs are mobile robots with the ability to move in predetermined places, autonomously and without running the risk of colliding with other elements around them. Easily programmable, they perform the transport of heavy loads, unhealthy tasks and are capable of working 24/7 [16].

Industry 4.0, is a term designated to explain the application of new technologies in key industrial processes. Increasingly, advanced tools, software and equipment are being incorporated into companies, transforming production methods and management in manufacturing [17]. A large share that self-guided vehicles in Industry 4.0. They represent an ideal first step towards automation, also serving to complement other automated systems in logistics and production. By integrating AGVs into industry, a company has the opportunity to adjust its production processes to a completely new structure. In this way, these processes can be adapted to customer requirements or to a new market situation. Among the main benefits that this technology offers, we can highlight: increase in productivity and cost reduction, decrease in the number of failures, increase in customization capacity, greater competitiveness, safety for the employee and for the goods [18].

The factory of the future is already a reality, so the older technologies have begun to be replaced by newer ones, which include more sophisticated resources, similar to the technology used in navigation applications that calculate their own route, and are able to generate more agility and better use of human resources in more strategic tasks. All this, besides reducing costs, generates better results [19].

The AGV, or Autonomous Guided Vehicle, is an older technology that is guided by tracks, guides, or magnetic tapes, and therefore requires a controlled environment to function [20].

AVGs were pretty much the only option for automating the transportation of materials within industries. However, with technological advances and the increasingly latent need to adapt to Industry 4.0, these models have evolved until they arrived to more intelligent ones [21].

The AMR or Autonomous Mobile Robots type robots, which are fully autonomous robots, as they navigate from sensors and scanners present in their components. They are easily programmable and do not need a special ambient structure to function [22].

AMRs, are endowed with software-based intelligence with maps that are preloaded, camera images and sensor data, which make it capable of even choosing the best route for the transportation that should be performed [23].

One of the differentiators of the AMR is that it is an IoT device. It is possible to extract data from it for information and is able to do monitoring regardless of where it is at all times. The AGV does not have this kind of technology [24].

The IoT (Internet of Things) is the virtual connection between objects in the analog world with the internet, making them smarter. With this technology, AMR robots become much easier to program and consequently more flexible.

Constant technological innovations and the need to adapt to change in an agile way is one of the characteristics of Industry 4.0. In this context, AMR's ability to adapt to new routines and configurations makes advances and improvements even more dynamic, helping the industry to innovate more and more.

In other words, if there is a need for changes in the factory infrastructure or production processes to apply continuous product improvements, the flexibility of AMR makes it possible to modify their "routes" instantly, following the movement of the factory.

AMR robots have a few more differentiators besides ease of operation and flexibility. The technology applied to them makes it possible, for example, that in the case of the appearance of an obstacle or employee in front of the equipment, it deviates from the blockage and continues its route without threatening its own safety and that of the people around it.

Another AMR differential is the maneuvering space, which can be smaller than the space required when the AGV is being used. This is due to the fact that it is able to rotate 360° on its axis, eliminating the need for maneuvering [25]. Once the information on how to pick up and load the cargo to be transported is programmed, based on the information collected through cameras and sensors through software, it is possible to control a fleet of AMR robots making them prioritize the most appropriate tasks according to the location and availability of each one [26].

The AMR robots are more flexible and safer, and offer a simpler implementation, because they do not require preparation of the environment, the solution becomes even less expensive, although more advanced. With its low implementation cost and fast process optimization, AMR technology brings more efficiency practically immediately and with an ROI (Return on Investment) in much less time, usually in less than 6 months.

Combined with its adaptability and safety, the applications of AMR equipment become almost limitless, and are able to meet the needs of any type of industry. Not to mention the possibility of better utilization of your company's human capital and consequent increase in productivity.

One of the main problems encountered in the development of self-guided autonomous robots is their navigation, methods related to navigation have been proposed over the years. Location is an essential indoor information for robot navigation systems. In autonomous navigation, the robot must maintain knowledge of its position and orientation over time [27]. The precise knowledge of the location in relation to the environment is fundamental for the robot to calculate its trajectory to perform a given task [28]. An imprecise or uncertain location can cause situations in which the robot does not perform its tasks efficiently, which can make it idle [29].

The set of information needed to determine the location of robotic platforms comes from successive observations of sensors embedded in the robot itself.

One of the most common ways to obtain the location of the robot is to use triangulation. This mechanism, however, presents an increasing inaccuracy over time and a high sensitivity to the type of sidewalk. Thus, it is common to associate other sensors to collect data on the position and orientation of the robot, such as video cameras, lasers, Global Positioning Satellite System (GNSS), ultrasonic sensors, and inertial sensors. The combined use of several sensors for localization makes it difficult to deal with the different uncertainties and inaccuracies of each sensor, to eliminate the perturbations occasionally caused by the sensors, and to determine the most appropriate observation and movement model [28]. The challenge of locating people or objects is practically divided in the insertion scenario, being them: location systems in external environments (outdoor), and location systems in indoor environments [30]. Indoor localization has unique variables and new challenges when compared to outdoor ones, resulting largely in function of the Global Positioning System (GPS) not working satisfactorily indoors [31]. This work seeks to develop a method for navigation of AMR robots in indoor environments.

II. LITERATURE REVIEW

There are several activities that can make use of applications that determine the location indoors. This is the case in hospitals, where it is common to have urgent or emergency cases, which demand to know where the doctors are. Another example is the case of companies, industrial parks, cargo warehouses, etc., where it is desired to know where a certain employee is. There are also cases of targeted marketing and advertisements, where one can generate a notification, in a smart phone for example, if the user is passing close to a store or product in a shopping mall. This dissertation is focused on the methods, techniques and tools to help the development of products and robots that need to work with location precision in internal environments, besides presenting the main technologies related to the theme, with their respective advantages, disadvantages, challenges, and finally the prototype of a mobile robot will be proposed and developed, using one of these techniques.

2.1 Localization techniques

Location systems can be organized into categories according to different techniques, which are used to estimate the location of mobile devices. A localization system generically consists of 3 different entities, fixed sensors, mobile modules, and a network management element or sensors when they exist. The mobile modules are monitored by fixed units that are usually placed in higher positions (sometimes on the ceiling). Their location is made from the monitoring information, by the network itself or by a microcontrolled or microprocessor system [32].

2.2 Direct identification

This localization technique is related to the detection of objects through their proximity to reference devices (mobile device facing a given sensor). Examples of this localization technique are infrared-based systems, in which an emitter is identified near a given sensor. Another example is the case of systems based on RFID (radio-frequency identification) present, for example, in cards that allow to identify a person, through its passage in a sensor [33].

2.3 Time acquisition

The concept of device localization by time acquisition consists of measuring the propagation time of the signal between the sender and several receivers. Through this same measurement, and knowing the speed of propagation of this signal in advance, it is possible to estimate the distance from the locatable device to various reference points. There are several techniques based on this concept, such as: Time-of-Arrival (ToA), Times-Difference of Arrival (TDoA) and Time-of-Flight (ToF) [34].

Time-of Arrival (ToA): As the name implies, this technique is based on measuring the time of arrival of a signal between the transmitter and the receiver. The transmission time is determined from the value of the transmission instant and the ToA (time of arrival) marked by the receiver. This technique requires network synchronization, since a deviation of 1μs in the time measurement could impose errors of hundreds of meters [35].

Times-Difference of Arrival (TDoA): This technique is based on acquiring the transmission time, rather than calculating it from two instants. For this purpose, these systems usually use two different technologies with different propagation speeds. The technology with the higher propagation speed is used to signal the beginning of the time count, while the reception of the second signal terminates the time count, giving rise to the TDoA. From the propagation speed of the second signal, a distance-time relationship is achieved [36].

Time-of-Flight (ToF): This technique has great ease of implementation. It is a technique for measuring the communication time between two points. In this method, the sender starts time counting at the instant it transmits a signal, ending this counting at the instant it receives the response. After compensating for the processing time (tP) of the receiver and dividing the corrected time between the two directions of communication, the sender determines the transmission time (tT), which will be used to calculate distances and determine the relative positions of the sender and receiver [37].

2.4 Outdoor positioning system

The main outdoor positioning systems are GPS (North American Global Positioning System) and GLONASS (Russian Global Navigation Satellite System). Both make use of satellites that provide time information and atmospheric data [38].

2.5 What a GPS does

GPS (Global Positioning System) is a device that originated in the United States Department of Defense. Its function is to identify the location of a device called a GPS receiver. [39].

The receiver devices, in turn, have the function of sending a signal to the satellites. Thus, making some calculations, which you can see below, the GPS receiver can determine what your position is and, with the help of some city maps, indicate which paths you can take to reach the desired location [40].

The principle of operation of these positioning systems is in measuring the time it takes for the signal emitted by each satellite to find the receiving antenna [41].

The speed of signal propagation in vacuum is approximately 300000km/s, if the time required for the signal to reach the receiving antenna is known one can obtain the distance between the satellite and the receiver [42].

For GPS to work properly, it is necessary to use three components, called: spatial, control and user. The spatial one is composed of twenty-seven satellites that are in orbit. Twenty-four of them are active and three are the "reserves", which come into operation if there is a failure with one of the main satellites [43].

The arrangement of these satellites in orbit ensures that there are always at least four of them available anywhere on the planet. Thus, whenever you and a person living in Japan are using GPS, they will certainly be able to use the device without a problem [44].

The second component, control, is nothing more than satellite control stations. In all there are five stations spread around the globe. Their main function is to update the current position of the satellites and synchronize the atomic clock present in each of the satellites [45].

The last but not least component is the GPS receiver, and this is the only one of the three that we, the users, must purchase in order to use this wonder of technology. A GPS receiver is nothing more than a device that displays your position, time, and other features that vary from device to device [46].

An outdoor positioning system with an accuracy of 1 meter must have a time measurement with an accuracy of 3 to 4 nanoseconds [47].

Thus, it is necessary for satellites to have extremely accurate clocks. The signal propagation time is very small, on the order of 0.06 seconds if the satellite is on top of the receiver [48].

The accuracy of the satellite clock is obtained from atomic clocks, which use a resonant frequency pattern as a counter. This clock is based on a property of the atom, where the pattern is the frequency of oscillation of its energy. Every 9,192,631,770 oscillations of the cesium-133 atom the clock understands that one second has passed.

So that the clocks of the receivers do not affect the accuracy of the location, these are constantly updated with the atomic time transmitted by the satellites. Knowing the distance between the receiver and a satellite, it is only possible to state that the location is any point on an imaginary sphere with radius equal to that distance. If we know, however, the distance of the receiver from a second satellite, we know that the receiver's location is any point on the imaginary circle that results from the intersection of the two spheres, now bounded 4 in only two dimensions. With the distance value relative to a third satellite you get the intersection of yet another sphere, which results in only 2 possible locations. One of these points can be eliminated because it will be in space, leaving only 1 point that will indicate the position of the receiver [49].

2.6 Indoor positioning system

Due to the inefficiency of outdoor positioning systems inside buildings, specific positioning systems have been developed for indoor environments. The main technologies employed for indoors will be detailed below, being divided between those that do not use radio and wireless technologies [50].

2.7 Non-radio technologies

2.7.1 Magnetic Positioning

The Magnetic Positioning System is an indoor location method that does not use radio waves, but is virtually based on the variation in the Earth's magnetic field that can be monitored by a magnetometer, present in most of today's devices. Normally, the Earth's magnetic field is used only to obtain direction, but researchers have developed a system that monitors variations in the magnetic field introduced by concrete walls and other man-made obstacles, which together with the good sensitivity of the magnetometers used in current devices allows to determine the position inside indoor environments with an accuracy of up to 10 centimeters, working very well as a kind of GPS for indoor environments [51].

2.7.2 Inertial Systems

It can be used to measure the steps of an individual through a sensor that can be cross-referenced with maps to obtain the position of the mobile. Inertial navigation systems are usually equipped with at least two types of sensors: accelerometers and gyroscopes, The MPU-6050 sensor has in a single integrated circuit an accelerometer and a gyroscope, all 6 degrees of freedom, Figure 1. The accelerometers measure the acceleration force. The gyroscopes give the orientation of a given object [52].

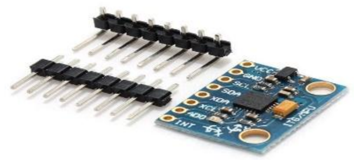


Figure 1 - Accelerometer and 3-axis Gyroscope MPU - 6050.
Source: [53].

Devices commonly used for wireless networking include laptop computers, desktop computers, cell phones, and others. Wireless networks work similarly to wired networks, however, wireless networks must convert information signals into a form suitable for transmission over the airborne medium [54].

Wireless networks serve many purposes. In some cases, they are used to replace the cable network or when the infrastructure does not allow for their installation, while in other cases they are used to provide access to corporate data from remote locations. Wireless infrastructure can be built at a very low cost compared to wired networking [55].

Wireless networks provide people with cheaper access to information. The time and effort saved by having access to the global network of information translates into wealth on a local scale, as more work can be done in less time and with less effort. Wireless networks allow remote devices to connect without difficulty, regardless of whether those devices are a few meters or several kilometers away. This has made the use of this technology very popular, spreading rapidly [56]. There are many technologies that differ in the transmission frequency used, speed and range of their transmissions. On the other hand, there are some issues related to the regulation of emissions within the electromagnetic spectrum. Electromagnetic waves are transmitted through various devices, but eventually these devices are subject to interference during transmission / reception. For this reason, all countries need regulations that define the frequency ranges and permitted transmission power for each technology. Wireless sensor networks (WSN) are in growing development and their use has been increasing in several sectors of society due to the ability to monitor and control environments without the need for a physical connection between their devices [57]. Wireless communication (or wireless) is used in networks such as WPANs (Wireless Personal Area Network), WLANs (Wireless Local Area Network), WMANs (Wireless Metropolitan Area Network) and WWANs (Wireless Wide Area Network), where each classification varies according to the application area and signal range [58], according to figure 2.

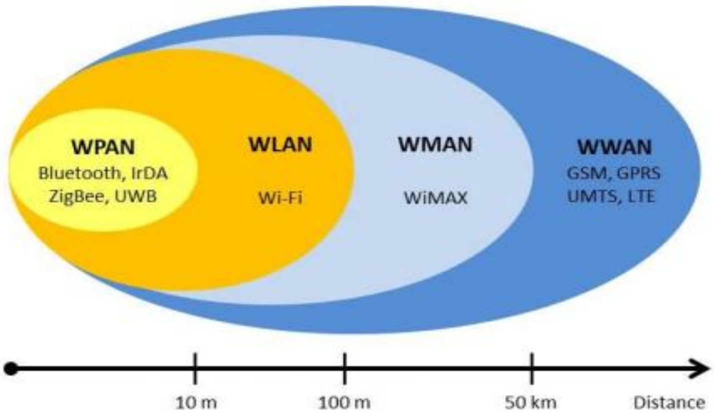


Figure 2 - Classification of wireless networks.
Source: [58].

WWAN consists of wireless networks capable of spanning a large geographical area from antennas or satellites. Wireless Metropolitan Area Network (WMAN) allows you to connect different locations in a metropolitan area (e.g. office buildings in a city), using fiber optic or copper cables and dedicated lines. Wireless Local Area Network (WLAN) covers only a limited area, equivalent to a room or offices [59].

2.7.4 Wifi

The Wifi technology allows the connection between different points without the need for wires, through devices that use radio frequency or light as infrared. Among the main wireless technologies we have [60]:

IrDA - (Infrared Dada Associations) - Transmission bus through infrared light. Through light signals emitted from an infrared LED (light emitting diode), data transmission is made. These signals are captured by a sensor present in the device, the receiver [61]. Despite being a cheap interface, its data transmission speed is low, reaching up to 115 kpbs. Its mobility is also limited, since it has a range of no more than 2 meters and needs line of sight, without obstacles, i.e., the devices need to be pointed at each other for data transmission. This system is commonly used in TV remote controls [62]:

IrDA-D - Oriented to connection between devices for data transfer;

IrDA-C - Oriented to command and control.

Wifi - (Wireless Fidelity) - Licensed by the Wi-Fi Alliance to describe embedded wireless networking technology (WLAN) based on the IEEE 802.11 standard. WiFi, based on the IEEE 802.11

standard, operates in the ISM (Industrial, Scientific and Medical) bands with the following ranges: 902 MHz - 928 MHz; 2.4 GHz - 2.485 GHz 8 and 5.15 GHz - 5.825 GHz (depending on the country, these limits may vary). The access point transmits the wireless signal over a short distance, usually up to 100 meters, but if the network is IEEE 802.11n standard, the distance can be up to 400 meters, Table 1 [63].

Table 1 - IEEE 802.11 comparative table.

IEEE 802.11	Frequency	Transmission rate	Compatibility	Indoor/outdoor range
802.11b	2.4 GHz	11 Mbps	✓	30m / 160m
802.11a	5 GHz	54 Mbps	-	15m / 80m
802.11g	2.4 GHz	54 Mbps	✓	
802.11h	5 GHz	54 Mbps	-	15m / 80m
802.11n	2.4 GHz / 5 GHz	300 – 600 Mbps	✓	400m / -

Source: [63].

2.7.5 Bluetooth

Bluetooth, also known as IEEE 802.15.1, was developed by the Ericsson company in 1994 [64]. It works on the ISM (Industrial, Scientific and Medical) frequency of 2.4GHz and low range (depending on power: 1 meter, 10 meters, 100 meters). It is characterized by its robustness, low consumption, and accessible cost. Since they use radio communication system, no line of sight is required between transmitter and receiver, only a minimum receiving power for operation [65]. The communication of Bluetooth devices is characterized by the master/slave principle, and can be done through two types of topologies: the piconet and the scatternet, figure 3 [66].

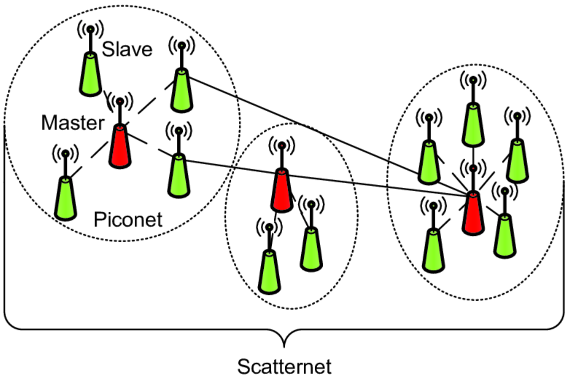


Figure 3 - Bluetooth topologies.
Source: [67].

The devices can connect together to form networks limited to 8 nodes, known as piconets, where one is the master node and the rest are active slave nodes, which can be located within a coverage radius of up to 10m. In this topology, all members of the communication are synchronized using the master's clock, which is responsible for allocating or blocking new connections. The communication from master to slaves can be point to point or multipoint [68].

To reduce power consumption, the slave devices can operate in standby mode. Another topology, called scatternet, being the overlapping of several piconets in order to form larger structures [69]. A slave can belong to several piconets. When leaving a piconet, the slave must inform the master that it will not be available for a certain period of time, however the rest in the piconet continue their communication normally. If the master leaves the piconet, the piconet remains unavailable until it returns to it [70] as shown in Figure 4.

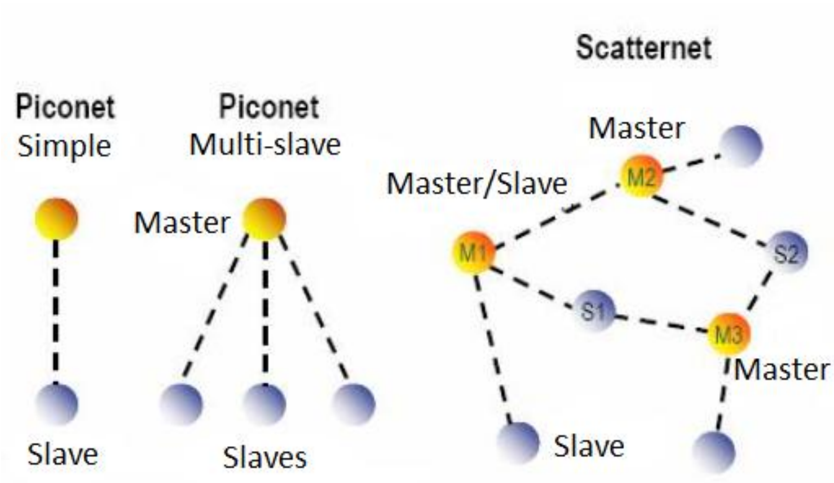


Figure 4 - Bluetooth configuration depending on the connection.
Source: [71].

2.7.6 ZigBee

The ZigBee network is a set of specifications for personal wireless networks (WPAN), i.e., digital radio connections between computers. WPAN has a low data transfer rate. ZigBee is a low data transfer rate, low noise, low power consumption WPAN network, thus characterized by long battery life. The ZigBee Alliance, the body that defines the ZigBee standards, also publishes application profiles that allow various vendors to create interoperable products that work at this frequency, [72].

The foundations of the technology that is now known as ZigBee were created and established by the Institute of Electrical and Electronics Engineers (IEEE). The name comes from the analogy between the operation of a mesh network and the way bees work and move, Figure 5 shows a Zigbee module that is often used in IoT projects.

Figure 5 - Xbee Zigbee module.
Source: [73].

Bees live in a hive and fly in a zigzag pattern. When they fly in search of nectar they communicate with other bees in the same hive, transmitting information about distance, direction, and food locations. Putting zig zag together with the English translation of bee, ZigBee was born. ZigBee is a wireless networking protocol intended for IoT devices, focusing on low-power devices, [74].

The philosophy of ZigBee differs from existing wireless networks, such as WiFi or Bluetooth, as it does not use high bandwidth for the transmission of large amounts of data, but rather reliable communication coupled with extremely low power consumption [75]. It has low transmission rates for monitoring and control applications, which make it possible to use batteries as a power source for the devices. The protocol transmits data via radio waves at a frequency of 2.4GHz with immunity and no interference transmitting data at transfer rates between 20kbit/s and 250kbit/s [76]. The topologies are shown in Figure 6.

Star: In the star topology there is a central device that controls the entire network, managing communication between stations.

Mesh: In the mesh topology all devices can help manage the network, i.e. there is more than one connection between devices.

Tree: While in the tree topology is an equivalent of several star networks interconnected through their central nodes.

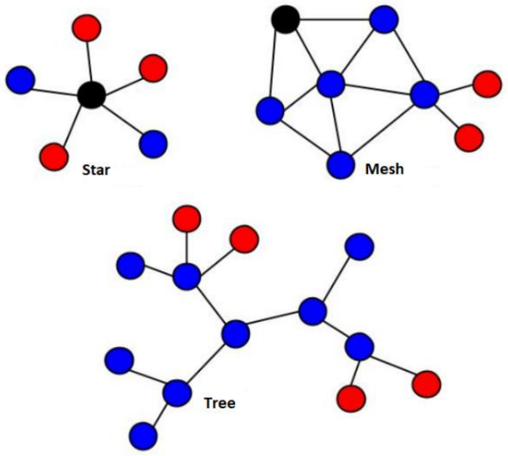


Figure 6 - Building the ZigBee network topologies. Source: [77].

2.7.7 RSSI

This method uses Received Signal Strength Indication (RSSI) analysis at the receiver and a model that describes how it varies with distance. The transmitted signal undergoes attenuation during its path, decreasing its power proportionally to the distance traveled [78]. The technique allows the location of a mobile module to be determined as being in the proximity of a sensor, through RSSI values, or through the distances estimated by three sensors, from the acquired RRSI values. The intersection of three circles, each with its center at a different sensor, delimits a small area where the mobile module is most likely to be found. This method is referred to as triangulation [79]. RSSI-based device localization can be more accurate when performed according to the fingerprinting method. This method comprises two phases. The offline phase and the online phase. In the offline phase the RSSI is measured on a grid of points in an area of interest, while the online phase uses this same grid to create the parameters of the propagation model. The higher the number of points used to create the model, the better the calibration, but also the higher the expense. This technique also has the disadvantage of being a time consuming process and every time the area of interest is changed the model created must be changed, [80].

2.8 Localization techniques

GPS is not successful for location in Indoor environments, due to the construction of the site, the signal can be weak or even non-existent, thus affecting the accuracy of the position. Nowadays, some techniques are used for navigation in Indoor environments [81]. All the positioning systems described in the previous section can use different localization techniques to estimate the position of the mobile device in Indoor environments. In this section the main existing techniques will be addressed: proximity, trilateration, triangulation and fingerprinting.

2.8.1 Proximity

In the proximity technique the object to be located is discovered by the closest reference point, that is, by knowing the location of the reference points we know the location of the object. This method can be obtained through 3 processes: physical contact, monitoring of wireless access points, and observation of automatic identification systems. Physical contact consists in detecting the physical touch between the object to be located and the reference point. The reference point can be based on pressure or touch sensors. By knowing the position of the reference point it is possible to know the position of the object to locate.

The wireless access point monitoring method consists of a mobile device detecting one or more access points. If the device detects more than one access point, it uses the maximum RSSI (Received Signal Strength Indicator) value to choose the access point to which it will connect. Observation of automatic identification systems is the method where from the person's actions you can estimate his or her position. For example, when making a payment with a credit card, registering for landlines, passing tolls, etc. That is, a person using the card in an ATM terminal it is possible to know when and where it was used, and the location of the user can be estimated.

The simplest indoor positioning technique is through a proximity detector placed at a specific position in the environment. In this way, when the user is within the range of the detector, if the location of the figure 10 reference points is known, the position of the mobile is known. This method can be done through 3 processes: physical contact, wireless access points monitoring and automatic identification system observation [81] as shown in figure 7.

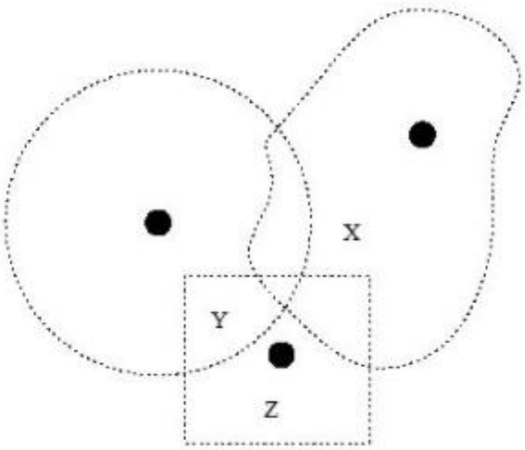


Figure 7 - Location by proximity, monitoring by points.
Source: Authors, (2021).

In the physical contact process, the position of the mobile is made with the detection of physical touch between the mobile and the reference point, composed of pressure or touch sensors. The wireless access point monitoring method, on the other hand, is based on the detection of access points by the mobile device. If more than one access point is detected, the closest point to the mobile is obtained by measuring the maximum signal strength (RSSI) [82]. In the automatic identification method the position is estimated from the actions of people.

2.8.2 Triangulation

The triangulation technique uses the geometric properties of triangles to estimate the location of the target, [83]. It has two derivations, one of which is lateration, which estimates the position of a device by measuring the distances to various reference points. These reference points are signal transmitters and their location must be known. The user's position can be calculated based on the measurement of the distance between the reference point and its location, figure 8. After this measurement a circle is created where the radius has precisely that same measurement, the center of the circle is the reference point. This procedure must also be done for the other two reference points, after having the three circles it is possible to know the intersection between them, that intersection is the position of the user, [83].

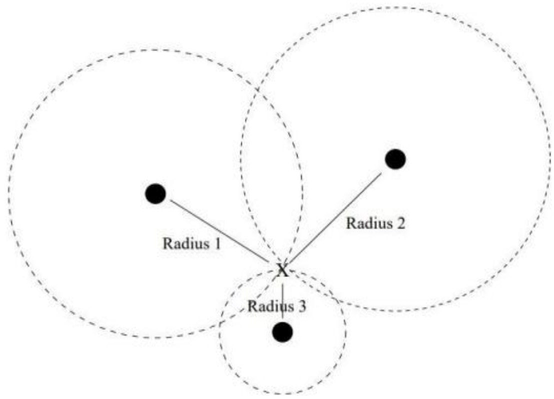


Figure 8 - Triangulation technique.
Source: [83].

2.8.3 Trilateration

It is the most basic and intuitive method, it is used when the positions of three references and their distances to the point you want to estimate are known, as shown in Figure 9, It can be stated that trilateration is given by the intersection of three circles centered on the position of the references, having the radius equal to each range measurement, [84].

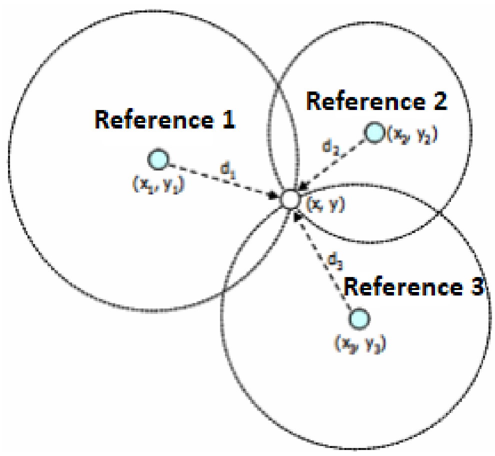


Figure 9 -Trilateration.
Source: [83].

2.8.4 Fingerprinting

The fingerprinting positioning technique consists in the analysis of a single feature of a scenario, where this feature is collected and then compared with the existing data in the database for each scenario. Thus, this technique is composed of two phases: a calibration phase (offline) and a comparison phase (online) [85]. In the offline phase, information is collected about the signal strength received by the mobile receiver with respect to each of the transmitter bases at various points in the desired environment. The data collected in this phase is stored in a database. Each location should contain a list of the signal strength values for all visible access points. This must be done, as the position of the user/mobile device can influence the values measured by the access point. Already in the online phase, a mobile receiver will collect information of signal intensities that should be compared with the values obtained in the propagation map, created in the previous phase, to estimate its position [85].

2.8.5 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a type of Bluetooth that is about 10% less energy-intensive than standard Bluetooth. This is because the latter was designed for data transmission only. BLE was also developed for data transmission, but with a strong bias towards maximizing battery savings, precisely to guarantee a long information transmission time. The BLE transmission protocol gained strength in 2010, with the appearance of its Bluetooth version 4.0. It has been in widespread use since then because it easily allows short to medium range wireless connections. Its characteristics make a BLE device act mostly in sleep mode (low power mode), being activated only to make connections lasting milliseconds. Thus, it is ideal for applications that information sporadically [71].

2.8.6 Beacons

A Beacon is a device that is able to give precise location in an indoor environment. Beacons are devices that emit a radio signal via bluetooth low energy (BLE) technology, also known as bluetooth 4.0. These signals can be picked up by smartphone and tablet applications, and can be interpreted as triggers for a certain action in an application. For ease of understanding it is as if Beacons were GPS for indoor environments, however, they cannot detect geographic location [86]. They can tell whether the device is near or far from the installed location. Beacons use Bluetooth Low Energy to detect the proximity of other devices and transmit a unique identifier number that is then received by the operating system of the device it is communicating with, the user only needs to be Wi-Fi connected in the location [87]. GPS is a device that performs location tracking for users in open environments and is very useful in traffic. Beacons have a different purpose. The signal emitted by them only has the ability to locate objectives indoors. Although the form of mapping is similar, both the signals emitted and what can be obtained through the two technologies are very different.

2.9 PID Control (Proportional, Integral and Derivative)

Proportional-Integral-Derivative (PID) control is the most widely used control algorithm in industry and has been used all over the world for industrial control systems. The popularity of PID controllers can be attributed in part to their robust performance over a wide range of operating conditions and in part to their functional simplicity, which allows engineers to operate them in a simple and straightforward manner.

As the name suggests, the PID algorithm is composed of three coefficients: proportional, integral, and derivative, which are varied to obtain the optimal response [88].

2.9.1 Definition of Control Terminologies

The control design process starts with the performance requirements. The performance control of the system is usually measured by applying a step function defined as a setpoint command, then the response of the process variable is measured. Generally, the response is quantified by the characteristics of the response waveform. The rise time is the time it takes for the system to go from 10% to 90% of the steady state, or final value. Percent Overshoot is the amount that the process variable exceeds the final value, expressed as a percentage of the final value [89]. Settling time is the time required for the process variable to get within a certain percentage (usually 5%) of the final value [90]. Steady-State error is the final difference between the process variables and the setpoint. Note that the exact definition of these quantities varies in the industry, Figure 10.

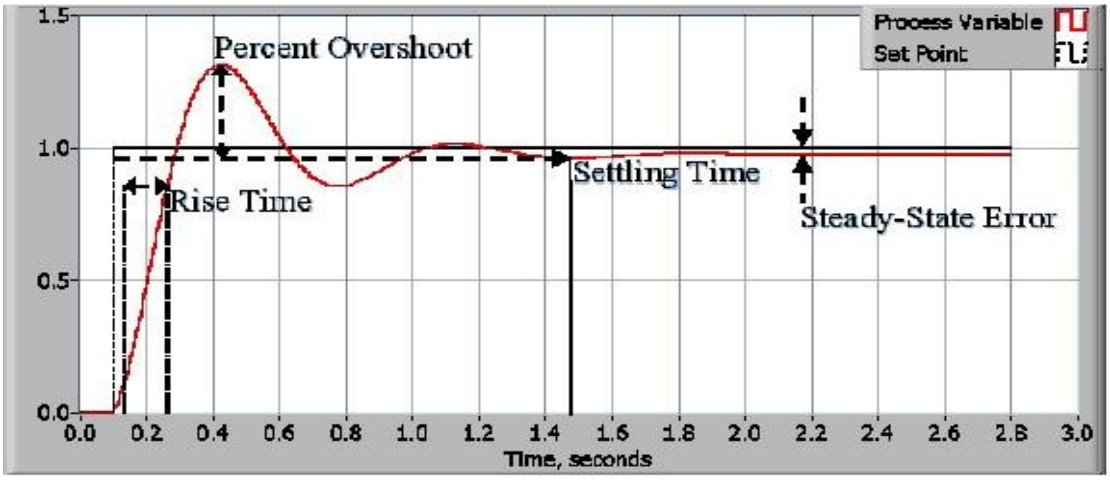


Figure 10 - Response of a closed-loop PID source.
Source: [91].

After using one or all of the parameters to define the performance requirements of a control system, it is important to define the worst-case conditions and the control system must meet these design requirements. Often, there is a disturbance in the system that affects the process variable or the measurement of the process variable. It is important to design a control system that responds satisfactorily under worst-case conditions. The measure of how well the control system is able to overcome the effects of disturbances is known as the disturbance rejection of the control system [92].

In some cases, the response of the system to a control output may change over time or with respect to some variables. A nonlinear system is a system in which the control parameters produce a desired response at one operating point and do not produce a satisfactory response with respect to another operating point. For example, a chamber partially filled with a liquid will exhibit a much faster response at the outlet of a heater than when it is more filled with this same liquid. The robustness of the control system is understood as the extent to which the system will tolerate disturbances and non-linearities. Some systems exhibit an undesirable behavior called deadtime. Deadtime is a delay between the time a change in the process variable occurs and when the change can be observed [93]. For example, if a temperature sensor is placed away from a cold water inlet valve it will not measure the temperature change immediately if the valve is opened or closed. Deadtime can also be caused by a system actuator or slow output taking time to respond to the control command. For example, a valve that is slow to open or close. A common source of deadtime in chemical plants is the delay caused by fluid flow through pipes. Loop cycle is also an important parameter of a closed-loop system. The Loop cycle is the time interval between calls to a control algorithm. Systems that change rapidly or have complex behaviors, require faster control loop rates [92].

2.9.2 Proportional Response

The proportional component depends only on the difference between the setpoint and the process variable. This difference is referred to as the error term. The proportional gain (Kc) determines the output response rate for the error signal. For example, if the error term has a magnitude of 10, a proportional gain of 5 would produce a proportional response of 50. In general, increasing the proportional gain will increase the speed of the control system response. However, if the proportional gain is too large, the process variable will begin to oscillate. If Kc is increased further, the oscillations will get larger and the system will become unstable and may even oscillate out of control [94].

2.9.3 Integral Response

The integral component adds up the error term over time. The result is that even a small error will cause the integral component to slowly increase. The integral response will increase over time unless the error is zero, so the effect is to drive the steady-state error to zero. The Steady-State error is the final difference between the process and set point variables. A phenomenon called integral windup occurs when integral action saturates a controller, without the controller adjusting the error signal to zero [95].

2.9.4 Response Derivative

The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the process variable. Increasing the derivative time parameter (Td) will cause the control system to react more strongly to changes in the error parameter by increasing the speed of the overall control response of the system. In practice, most control systems use very small derivative time (Td), because the response derivative is very sensitive to noise in the process variable signal. If the sensor feedback signal is noisy or if the control loop rate is too slow, the response derivative can make the control system unstable [96].

2.9.5 Adjustment

The process of optimal setting for the gains P, I and D to obtain an optimal response of a control system is called tuning. There are different tuning methods, the "guess and check" method and the Ziegler Nichols method, which is the most common error correction method in PID [97].

The gains of a PID controller can be obtained by the trial and error method. Once an engineer understands the meaning of each gain parameter, this method becomes relatively easy. In this method, the I and D terms are set to zero and the proportional gain is increased until the loop output begins to oscillate. When the proportional gain is increased, the system becomes faster, but care must be taken not to make it unstable. Once P has been set to obtain a desired fast response, the integral term is increased in order to stop oscillations. The integral term reduces the steady state error, but increases the overshoot. A certain overshoot value is always needed for a fast system so that it can respond to changes immediately. The integral term is again adjusted to achieve a minimum steady state error. Since P and I have been set so that the control system is fast with minimum steady state and constant, the derivative term is increased until the loop is acceptably fast relative to its reference point. Increasing the derivative term decreases overshoot, increasing gain, maintaining stability and yet making the system highly sensitive to noise. Often, the engineer has the need to make compensation for one characteristic of a control system to improve another, and thus meet his needs [98].

The Ziegler-Nichols method is another popular method of tuning a PID controller. It is very similar to the trial and error method, where I and D are set to zero and P is increased until the cycle begins to oscillate. Once the oscillation begins, the critical gain Kc and the period of oscillations Pc are noted. The P, I and D are then adjusted according to the table shown below [99].

Table 2 - Fitting a controller using the Ziegler-Nichols method.

Control	P	Ti	Td
P	0.5Kc	-	-
PI	0.45Kc	Pu/1.2	-
PID	0.60Kc	0.5Pc	Pc/8

Source: [99].

III. METHODOLOGY APPLIED

According to [100] several are the modalities of research that can be practiced, which implies epistemological, methodological and technical coherence, for its proper development. According to [101], scientific method is the set of processes or mental operations that we must employ in research. It is the line of reasoning adopted in the research process. [101] also states that the use of one or another method depends on many factors: the nature of the object we intend to research, the material resources available, the level of scope of the study and, above all, the philosophical inspiration of the researcher.

Thus, it is necessary to choose a method that is more appropriate to the context addressed and effectively enables the achievement of the expected results. According to [101] the hypothetico-deductive method begins with a problem or a gap in scientific knowledge, passing through the formulation of hypotheses and a process of deductive inference, which tests the prediction of the occurrence of phenomena covered by that hypothesis. From this viewpoint, we have that the research in question aims to generate knowledge for practical application, directed to the solution of specific problems, involving local truths and interests. What [101] points out as applied research.

As for the objectives of this research, [100] characterizes it as exploratory, for seeking only to raise information about a particular object, thus delimiting a field of work, mapping the conditions of manifestation of this object.

The experimental research model was adopted, as pointed out by [100], is the research that takes the object itself in its concreteness as a source and puts it under technical conditions of observation and experimental manipulation on the benches and boards of a laboratory, where suitable conditions are created for its treatment.

As for the research technique, the observation modality was used, which is every procedure that allows access to the studied phenomena. It is an essential step in any type or modality of research, as [100] points out.

3.1 Materials and Methods

Once the research guidelines, the approach and epistemological boundaries have been defined, the next step is to obtain the general characteristics of what, according to the adopted methodology, will be defined as the problem to be addressed.

To illustrate a general context of the study proposed in the project, we have a flow chart below, which points out the main stages of the process in question, figure 11.

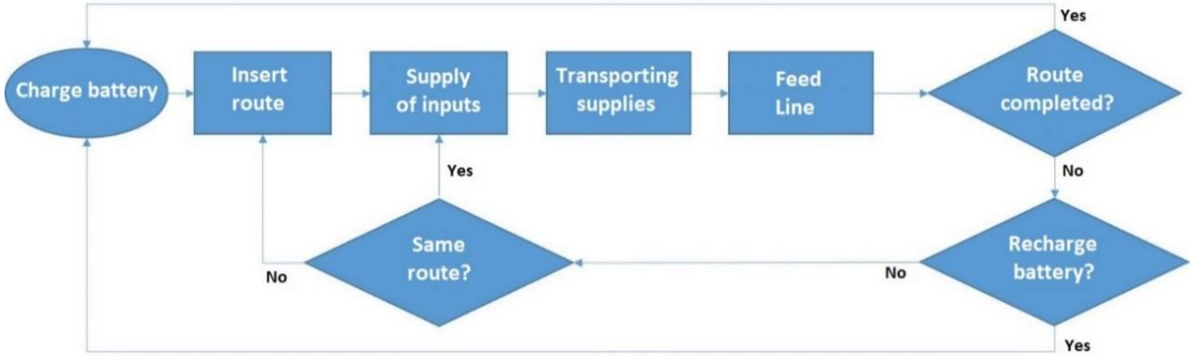


Figure 11 - Flow chart, illustration of the problem.
Source: Authors, (2021).

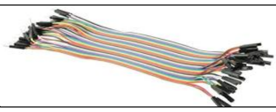
Thus, it is deduced then that to achieve the purpose of solving the problem, some procedures must be performed. The bibliographic study of reference sources in control and automation engineering, embedded systems and indoor localization methods and related areas is essential in order to satisfactorily obtain the components and theoretical bases for the development and improvement of the project. A trajectory management system will be developed during the project, as well as a battery management system. The trajectory management system will be responsible for informing the robot the route it must travel, and once in possession of the route the robot will search for the inputs to be transported, taking it to the production line. Once this transport task is accomplished, the robot will check the next task, getting the same route or a new one. If it does not have a new task it will go to its base to recharge its battery while waiting for the next task, figure 14. For the robot to be able to execute these tasks, performing them in the best way possible, it is necessary to develop all the robot's mechanical electronic structure as listed below.

3.2 Materials

Table 3 shows the items to be used in the proposed project.

Table 3 - Lists of materials used to build the prototype.

Item	Name	Description	Image

1	Lynxmotion aluminum chassis A4WD1	4WD differential drive system	
2	Sabertooth Dual 12A 6V-24V R/C Regenerative Motor Driver	Driver for controlling and driving the motors	
3	Arduino Mega Pro	Microcontrolled board. It has 54 I/O pins, of which 15 can be used as PWM.	
4	LIDAR-Lite 3 Laser Rangefinder	Laser system for collision avoidance.	
5	Marvelmind Starter Set HW v4.9-NIA (915MHz)	Beacon for indoor navigation	
6	Wires and Cables	Used for fixing the components	
7	Display LCD 20x4	Used to output information to track the receipt of data from Beacons	

Source: Authors, (2021).

Table 4 - Software tools used.

Tool	Concept	Project Application
SolidWorks	Software designed to create three-dimensional virtual mechanical prototypes. It is also possible to simulate the operation of parts, assemblies.	In the project, software was used to model all mechanical parts and devices. From three-dimensional prototypes, 2D drawings will be generated and forwarded for machining.
Proteus VSM 8.1	Software that allows you to create circuits, simulate and design layouts for analog and digital applications, including microcontrollers.	It will be applied to the development of electronic boards and connections.
VsCode	It is an integrated development interface (IDE). In this interface can be developed various types of software for different platforms. In the specific project we will use this platform we will use the PlatformIO plugin.	It will be used to develop the C code for the Arduino Mega Pro.
PlatformIO	It is a set of tools for developing embedded systems in C/C++. In June 2019 it became open source and full-featured for free.	Plugin for VsCode

Matlab	MATLAB is an interactive, high-performance software program for numerical computation. MATLAB integrates numerical analysis, matrix calculus, signal processing, and graphing.	Used to create and simulate the mathematical model of the robot.

Source: Authors, (2021).

Table 5 - Programming language for the Arduino Mega.

Technology	Concept	Project Application
C Language	It is a general-purpose, structured, imperative, procedural, compiled programming language.	In this project, it will be used for the development of the firmware and system module.

Source: Authors, (2021).

3.2.1 Prototype development

This chapter will detail the development of the main interfaces, both hardware and software, that will be used in this project. The microcontroller used is the Arduino with an ATmega2560 processor, containing 16 PWM lines and 4 pairs of serial communication, full duplex that can be set to 50000 bits per second, has an internal clock of 16Mhz, ideal for systems that need to acquire critical data, as is the case of this research.

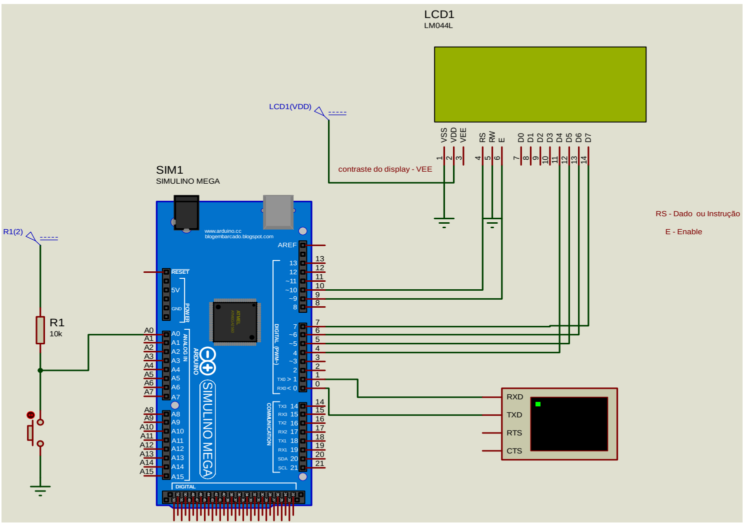


Figure 12 - Electronic circuit of the Arduino with the LCD.
Source: Authors, (2021).

Figure 12 shows the electrical circuit of the Arduino's interface with the liquid crystal display - LCD. This interface will serve to show the people who will handle the robot its route, its battery life, as well as information about its location, figure 13.

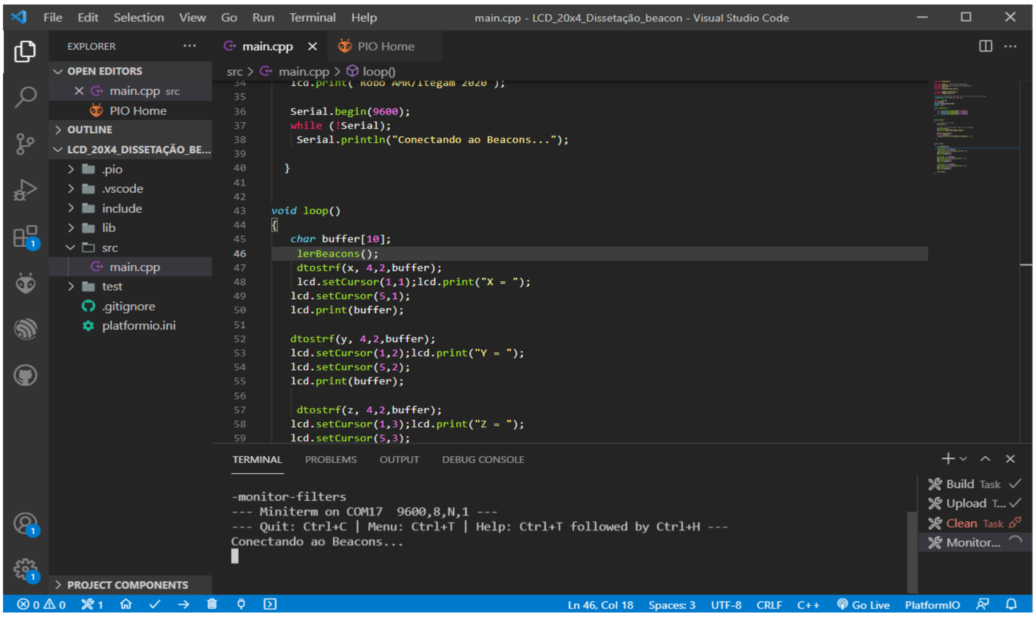


Figure 13 - Source code for writing to the LCD.
Source: Authors, (2021).

Figure 13, shows the source code of the LCD display, a function called "lcd." was created. To make it easier to communicate with the display hardware, as well as facilitate the development of the project. Figure 14 shows the result of this interface. Through the display the information that is processed can be visualized on the diplay.

Figure 14 - LCD showing the information obtained from the Beacon.
Source: Authors, (2021).

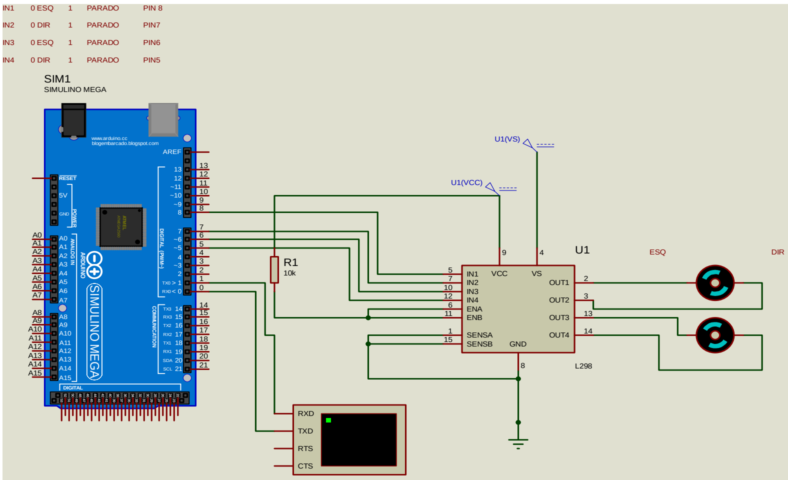


Figure 15 - Electronic circuit with Arduino to control the motors.
Source: Authors, (2021).

Figure 15 shows the software interface developed for the figure 18 motor driver, this code will use the intrinsic PWM functions of the Arduino's own library. Using this library provided by the Arduino makes it faster to develop applications that use motors.

3.2.2 PWM for controlling the robot motors

Pulse Width Modulation (PWM) (Figure 16) serves to control the amount of power delivered to the load. The PWM technique is widely applied in electronics, especially in switching power supplies. Besides this use, the PWM technique can also be used in motor speed control. For speed control of the motor driver (Sabertooth) we will use pins 13, 12, and 11 of the Arduino Mega, Figure 14. The PWM period is always constant 1.2ms, the PW pulse width has values from 1.5ms to 20ms, Figure 13. Depending on the configuration of the Sabertooth module, values ranging from 1.5 to 20ms can cause the motor to rotate clockwise or counterclockwise, the C language code for controlling the Sabertooth module is shown in Figure 15. PWM is the technique used to generate analog signals from a digital device such as a Microcontroller and it is so efficient that nowadays almost all modern Microcontrollers have dedicated hardware for PWM signal generation. In this article you will learn the basics of this technique and how it can be widely applied in the control of devices and even machines as occurs in the frequency inverter [102].

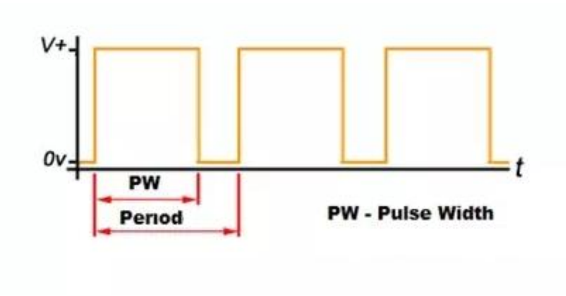


Figure 16 - Pulse width graph.
Source: Authors, (2021).

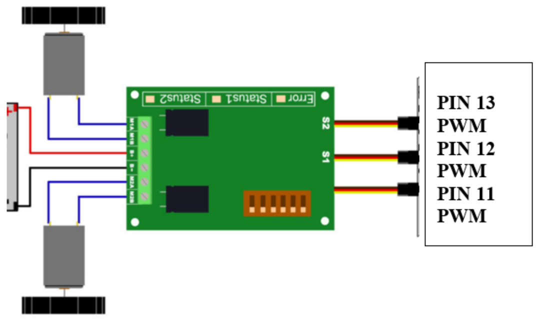


Figure 17 - Electrical connection between the Arduino and the Sabertooth module.
Source: Authors, (2021).

Figure 17 shows the code developed to manipulate the motors using PWM. The PWM is used to control the power sent to the motors, thus controlling the speed of the robot.

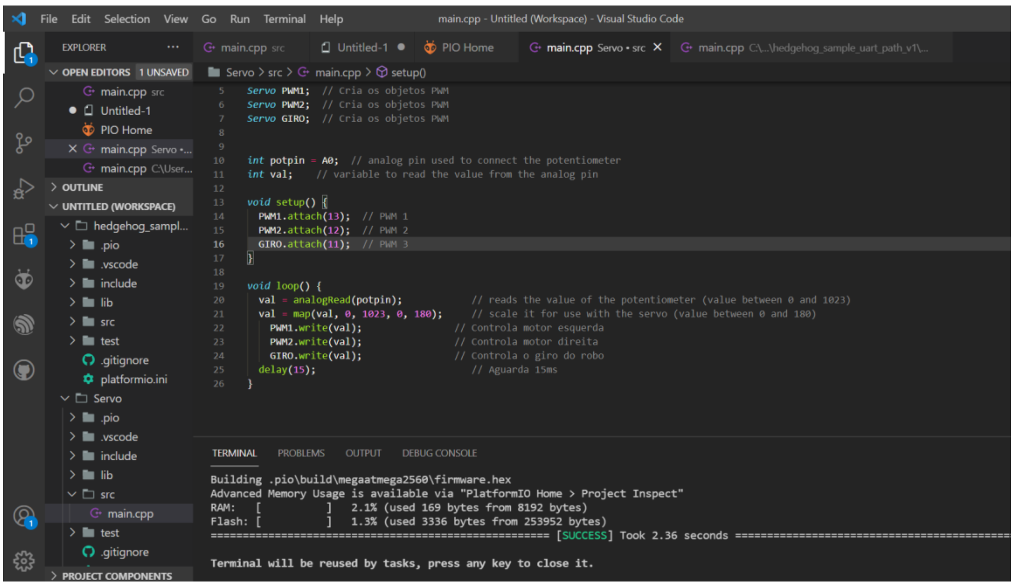


Figure 18 - C code for PWM control of the Arduino pins.
Source: Authors, (2021).

3.2.3 Controlling the motors through PID

Source code was developed to drive the motors, and automate the trajectory correction, as an example, code was first developed to drive/move the motors using PWM. After the tests the PID code was included. The adopted control algorithm had its parameters adjusted from the mathematical model of Ziegler - Nichols (modified), along with the accomplishment of the motors calibration, the better the adjustment of the following parameters (kp, ki, and kd) Figure 17, the better the PWM performance will be. The source code was planned in order to read the data obtained from the beacons, Figure 19, and through these position data received in real time, process and correct the route with the PID control so that the trajectory has the smallest possible error. Making corrections to the route automatically, and the calibration of the motors had been done previously in other experiments.

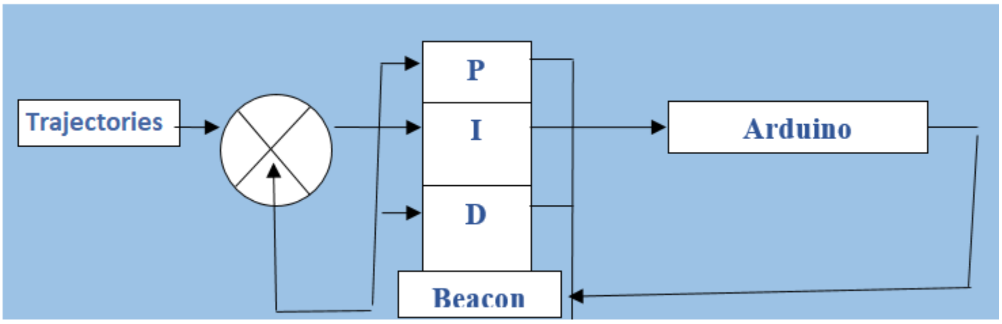


Figure 19 - PID Control Plant.
Source: Authors, (2021).

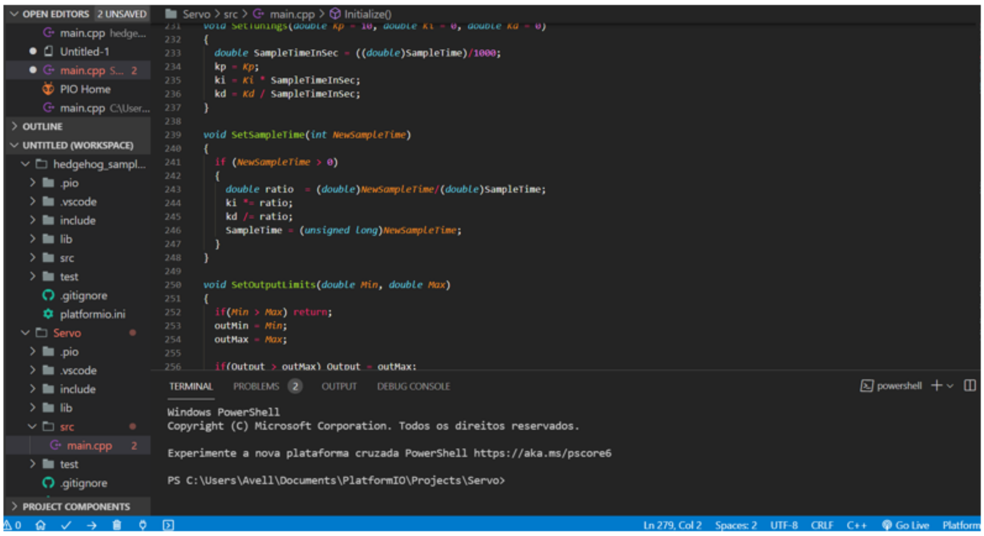


Figure 20 - Source code of the PID controller.
Source: Authors, (2021).

IV. RESULTS

The technology being developed for autonomous vehicles is quite impressive. In the near future we will have autonomous cars driving on ordinary highways with the safety and efficiency of the best human drivers. These autonomous vehicles use a variety of sensors to be able to locate themselves in any environment, they can also put together a very detailed plan to move from their current location to any desired destination. This paper shows an introduction on how these autonomous vehicles are able to follow their desired route in an indoor environment. The robotic perception system is intended to mimic the various components needed for humans to navigate their environment.

An important goal in the field of robotics is the creation of autonomous robots. Such robots must accept high-level descriptions of the tasks they are to perform, without the need for further human intervention. The input descriptions specify what the user wants done, not how to go about doing it. To do this, these robots are equipped with actuators and sensors under the control of a computer system [28].

The development of the technology needed for autonomous robots encompasses some ramifications such as automated reasoning, perception, and control, with several important problems arising. Among them is trajectory planning. In general, this problem consists of figuring out how to get an object from an initial configuration (position and direction) to a final configuration. A particular case of this problem is when the object to be moved is the robot itself [26].

In this work, methods are presented for the autonomous navigation of mobile robots in environments about which little or no information is available. The system operates in real time, using the robot's sonar to detect obstacles, and interacts with the robot's control system to track the desired trajectories.

An AMR robot can be considered an autonomous intelligent agent, equipped with sensors and actuators. Being an agent, the robot can interact with the environment where it navigates, that is, perform actions on it. An intelligent robot must take into account its perception capacity and its own state in order to make decisions about its actions. This therefore results in a cycle that involves preparing the environment, making a decision via an intelligent control system, performing the action, and finally perceiving the new configuration of the environment after the action. This structure governs the entire interaction between the agent and its environment, whatever the function performed. We can see from this the importance of sensors and actuators, and the control algorithm embedded in the robot, figure 21.

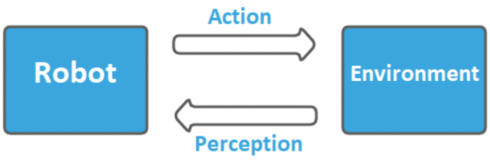


Figure 21 - Interaction of the robot with the environment.
Source: Authors, (2021).

There are numerous methods for locating mobile robots indoors. At the basis of all localization methods is the real-time measurement of one or more parameters, such as angles or distances. Through this measurement the location of the object is obtained, relative to one or more fixed points, whose location is known. These measurements are based on the physical properties of electromagnetic or ultrasonic signals, such as velocity or attenuation. The position of the object is then calculated using the measurements taken and the location of the known fixed positions. Using the indoor location data obtained from the beacon, the robot obtains in time its X0, Y0, Z0 position. Bearing in mind that the position to be reached is the X1, Y1, Z0 position (for navigation purposes this Z coordinate is irrelevant). First the distance D between the points P (X1, Y1) and P (X0, Y0) must be calculated. As seen before, as the robot moves there will be a natural tendency for it to go more to the right or more to the left, causing a variation in angle |Δθ|. Once the distance between the points is calculated, we can calculate angle θ. To achieve the goal P (X1, Y1), it is necessary to keep this angle constant during the journey between P0 and P1, Figure 22.

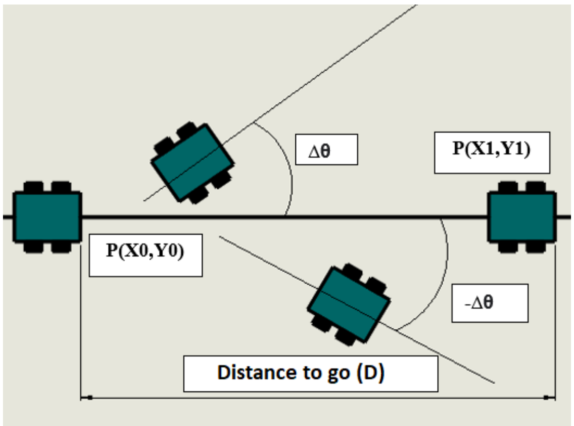


Figure 22 - Calculation of the robot trajectory.
Source: Authors, (2021).

During the trajectory the robot may assume different angles, these angles should be as close to zero as possible. Values of some too high cause an instability in the system. This can cause the robot to no longer return to its trajectory, figure 23.

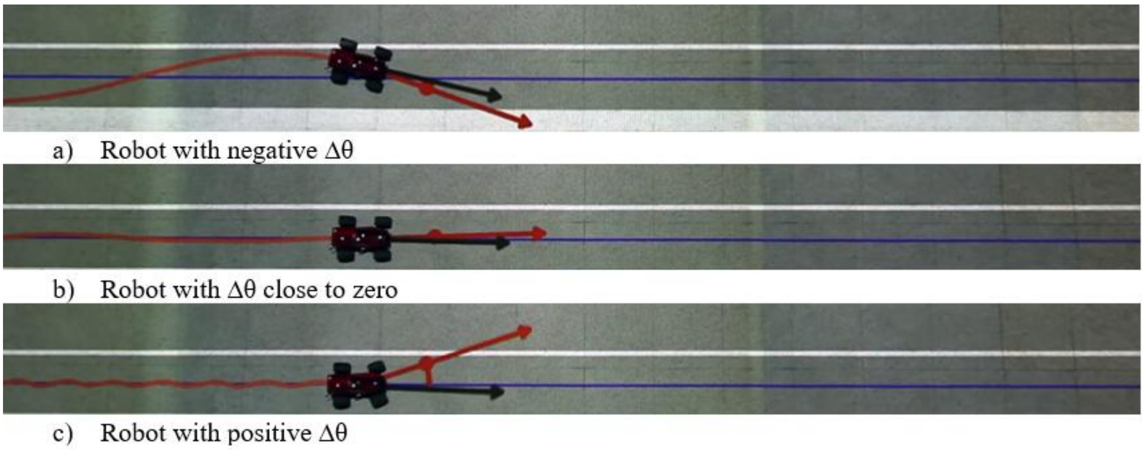


Figure 23 - Robot will be able to assume different angles during its trajectory.
Source: Authors, (2021).

Figure 24 shows the robot with a rather high Δθ angle, potentially leading to navigation instability.

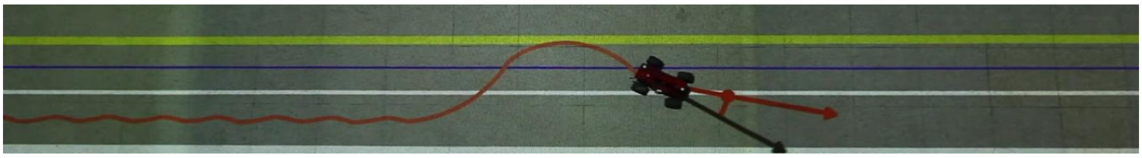


Figure 24 - High angle leading to instability in the robot's path.
Source: Authors, (2021).

Figure 25 shows an instability in navigation, the high Δθ angle made it impossible for the robot to return to its initial trajectory.

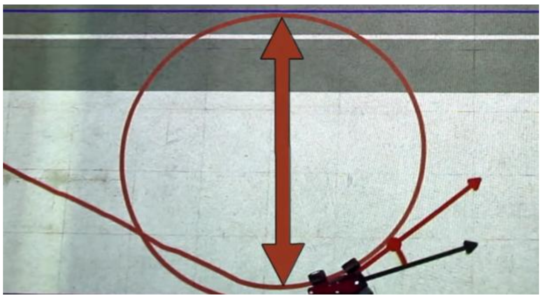


Figure 25 - Instability in the robot navigation.
Source: Authors, (2021).

To keep the angle Δθ close to zero the PID control was used, figure 26.

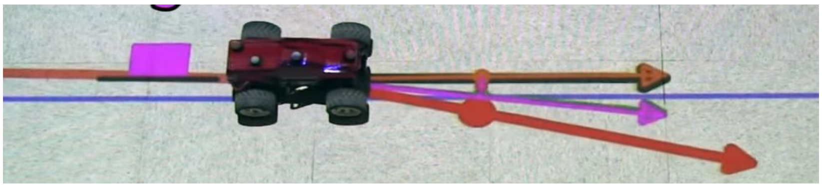


Figure 26 - PID control for system stabilization.
Source: Authors, (2021).

Initially we need to create a mathematical model for the mobile robot, figure 27, from this model the final project will be developed. To create a mathematical model we will initially equate assuming that the vehicle has only two wheels, a front one and a rear one.

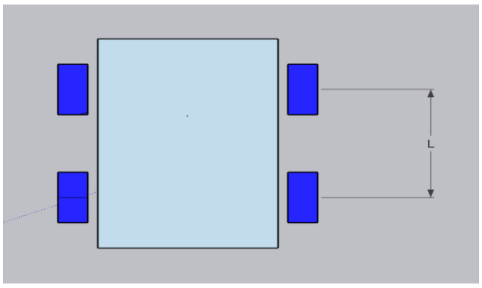


Figure 27 - Drawing of the robot with wheel distance.
Source: Authors, (2021).

4.1 Mathematical model

To create a mathematical model we will consider that the distance between the wheels of the robot is L. To obtain this model we will initially consider that the robot has only two wheels, this will simplify the mathematical equations figure 28.

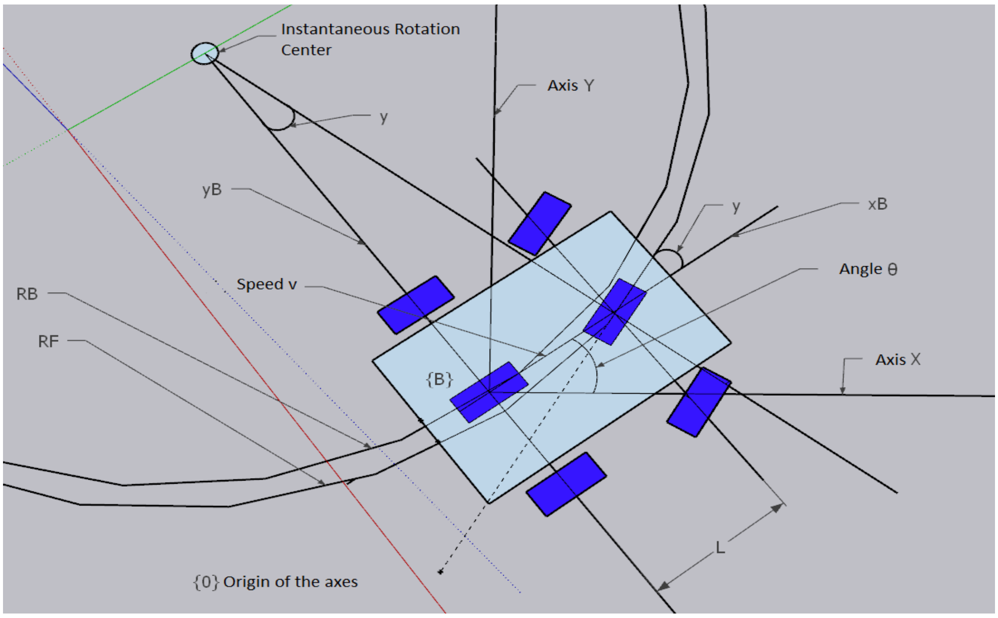


Figure 28 - Mathematical model of the ARM robot.
Source: Authors, (2021).

The initial position of the robot is represented by {0} origin of the axes, the wheels move through its center of rotation y, its angular velocity is given by:

$$\dot{\theta} = \frac{v}{R_B} \tag{1}$$

By simple geometry the turning radius RB = L/tan y, where L is the length between axes of the robot. For a fixed steering wheel angle the robot moves along a circular arc, for this reason curves on roads are circular arcs, we observe that the radius RF > RB, which means that the front wheel must follow a path, but long and consequently turns faster than the rear wheel. The velocity of the robot on each axis is given by (v cosθ, v senθ). Combining with Equation 1 we can write the equation of motion as:

$$\begin{aligned} \dot{x} &= v \cos\theta \\ \dot{y} &= v \sin\theta \\ \dot{\theta} &= \frac{v}{L}\tan\gamma \end{aligned} \tag{2}$$

This model, Figure 29, is known as the kinematic model because it describes the velocities of the vehicle, but not the forces or torques that cause the velocity. Equation 2 shows some other important characteristics of a car-like vehicle. When v= 0 then $\dot{\theta}=0$; that is, it is not possible to change the orientation of the vehicle when it is stationary. As we know from driving, we must move to turn.

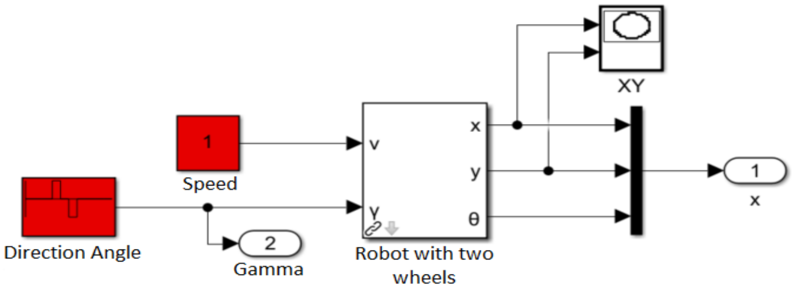


Figure 29 - Mathematical model of the two-wheeled robot vehicle.
Source: Authors, (2021).

The graph in figure 30 shows the speed, acceleration, and space traveled by the robot.

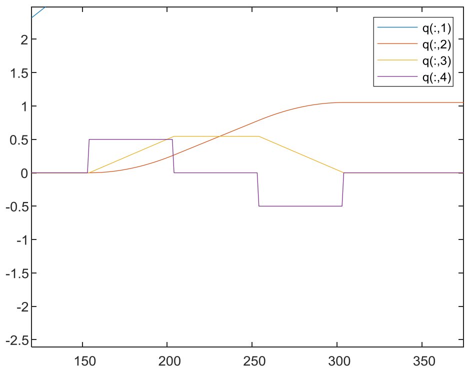


Figure 30 - Graph showing the output of the mathematical model.
Source: Authors, (2021).

When the steering angle $\gamma = \pi/2$ the front wheel is orthogonal to the rear wheel, the vehicle cannot move, thus an undefined region. We can then write an equation for the Y-component as a function of Equation 2.

$$\dot{y}\cos\theta - \dot{x}\sin\theta = 0 \qquad (3)$$

Using Equation 3 a model is implemented in MATLAB software, the speed input is a constant and the steering wheel spin angle is a finite positive pulse followed by a negative pulse, the model will simulate the motion of the robot. We will with consider the wheel distance of L =1 for simulation purposes.

Figure 31, shows the robot in position P0, in blue color the beacons strategically, the robot will receive the location information X, Y, Z by the beacons. The trajectory that the robot should travel are given by: P0, P1, P2, P3, P4, P5, P6, P7, P8 and returning again to P0. The yellow dots are obstacles along the path. The robot must follow the path without touching the obstacles. The trajectory shown in the figure is just an imaginary line. Once it gets the points P(X,Y), the robot will travel the distance between the points.

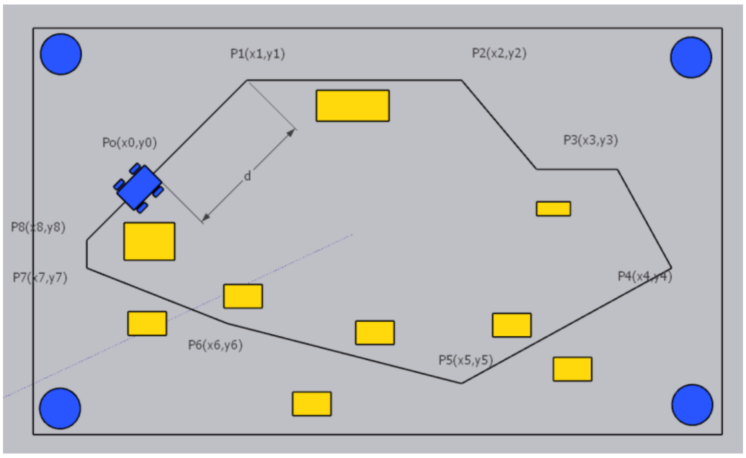


Figure 31 - ARM robot following a trajectory.
Source: Authors, (2021).

4.2 Following a Trajectory

The goal of the robot is to follow a predetermined imaginary trajectory, this trajectory is composed of points x,y as shown in figure 31. A simple algorithm of points (x(t), y(t)), points that must be traversed as a function of time. Through the receiver located on the robot, stationary beacons send the position information P0(x0,y0). To reach the points P1(x1,y2) it is enough to calculate the distance D (Equation 4) between point P0 and P1, also drawing a line between two points. The d* is the error that occurs when traversing the trajectory.

$$\boldsymbol{D} = \sqrt{(\boldsymbol{x1}^{*} - \boldsymbol{x2})^{2} + (\boldsymbol{y2} - \boldsymbol{y1})^{2}} - \boldsymbol{d}^{*} \qquad (4)$$

$$\boldsymbol{v}^{*} = \boldsymbol{k_v}\,e + \boldsymbol{k_i}\int e\,d\boldsymbol{t} \qquad (5)$$

To control the robot speed a PI (proportional-integral) controller is implemented, Equation 5. The speed acts for each new position is given by v* (current robot speed).

$$\boldsymbol{\theta}^{*} = \boldsymbol{tan}^{-1}\frac{\boldsymbol{y}^{*} - \boldsymbol{y}}{\boldsymbol{x}^{*} - \boldsymbol{x}} \qquad (6)$$

It is possible to calculate the angle θ* that the new position P* makes with the axis. A proportional controller is given by:

$$\boldsymbol{\gamma} = \boldsymbol{k_h}(\boldsymbol{\theta}^{*} - \boldsymbol{\theta})| \quad \boldsymbol{k_h} > 0 \qquad (7)$$

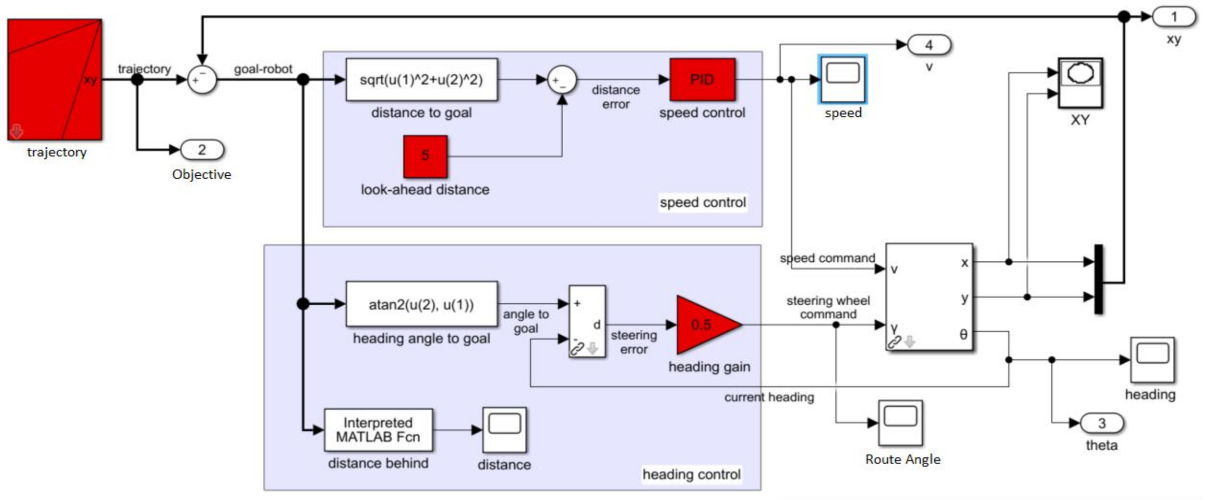


Figure 32 - Mathematical model with PI controller.
Source: Authors, (2021).

To validate the mathematical model some Cartesian coordinates listed in Table 5 were entered, Figure 33 shows the output graph of the mathematical model. We can verify from the graph that the trajectory is in agreement with the points (X,Y) in the table.

Table 6 - Cartesian coordinates for testing the robot.

[10 10; 20 40; 40 80; 90 80; 80 40; 30 10]

Source: Authors, (2021).

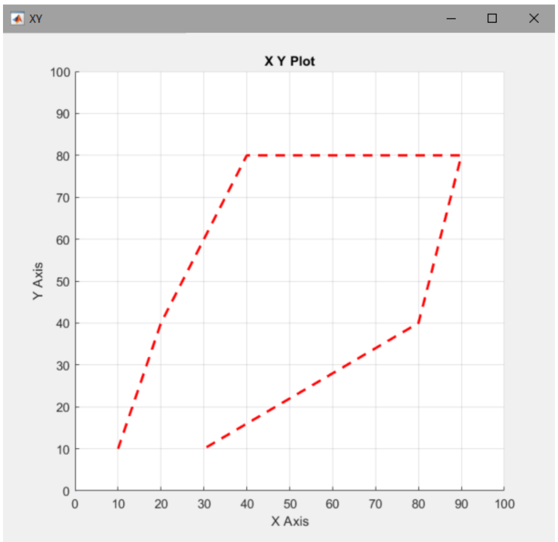


Figure 33 - Output graph of the robot with trajectory.
Source: Authors, (2021).

4.3 Validation test

The localization becons (Figure 34) and one installed on top of the robot, Figure 26, were placed in the test environment and validation of some obstacles in the robot's path, the robot should move while avoiding the obstacles. A video of the test can be seen at (https://youtu.be/4F7OVMLbuHk).

Figure 34 - Beacon installed in the robot.
Source: Authors, (2021).

Figure 35 - Validation test.
Source: Authors, (2021).

Figure 35, shows the validation test of the ARM robot prototype. The blue strip shows the trajectory of the robot, the image on the lower right side is the real time displacement. The circular objective beacons in green in the larger image, pass the robot the coordinates (X,Y,Z), for this project the Z axis was discarded since it is irrelevant.

V. CONCLUSION

Automatic line supply using intelligent ARM mobile robots is the solution for companies that need to transport materials and supplies within factories, since transporting materials does not add value to the company's products. The mobile robots will take the items to be produced to the assembly line and deliver them to other (static) robots or operators, using sensors they will be able to work together with people, the so-called collaborative robots. Several benefits are obtained with their use, the reduction of errors and losses - As the processes are digitalized, intelligent and autonomous, the precision is much higher. The operator does not have to look for references and locations in the middle of the stock, or count the necessary items on his own and take them out and put them on the line, for example. There is much less manual labor required, which reduces errors and waste. As a result, there is less need for rework, problems with misplacements, and other hindrances that can compromise deliveries, costs, and productivity. The processes will be more organized, without the use of paperwork and reports all controlled by software without the use of human intervention, since the robot having the location of where and to where it will search and deliver materials. We will have more agility in the delivery time of materials since there will be no stop in the delivery of products.

The processes will run automatically, without the need for order transmission, item search, and human displacement. The robots have a much higher work capacity than humans, with fewer breaks, faster displacement and higher load loading times. Greater safety, employees who used to perform unhealthy functions of transporting materials such as chemicals can be relocated to other functions, and the risk of accidents and injuries that are common in transportation due to weight and handling will be avoided. The company will be able to allocate employees to functions that are more motivating, of higher added value, and that are satisfying. With this, a greater productivity due to faster and more reliable processes, since we will no longer have line stops due to lack of materials or errors in the supply. Increasing the satisfaction of the final customer.

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