ACCOMPLISHING AND OPTIMIZING ROBOTIC SELF-NAVIGATION INTELLIGENCE FOR WAREHOUSE LOGISTICS THROUGH SENSOR FUSION AND ANTENNA LOCALIZATION

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Logistics automation has been the subject of many developments linking robotic hardware with improved quality and safety of work for warehouse employees. It is also a field where robotic navigation, route optimization and precise maneuvering are crucial to the competitiveness of the engineering product on the market. This research demonstrates a mathematical modeling method through which robots can navigate warehouse floors efficiently, using indoor positioning of high accuracy. Moreover, the paper also describes the hardware considerations taken into account when measuring the accuracy of the robot from achieving its destination on the floor plan. A prototype is creating, showing the sensor fusion interlinks for obstacle avoidance and distance mapping. Finally, the prototype and the algorithm are tested against eight static, as well as dynamic performance tests, in order to validate the performance of the system in static and dynamic interference environments. The goal of this paper is to present the engineering perspectives of optimizing a self-driving warehouse robot through utilization of the emerging technologies related to indoor positioning. This is presented through a prototype development of an Automated Guided Vehicle which will perform indoor positioning of itself across a warehouse floor plan and be able to avoid obstacles while driving towards its destination. Both the hardware description and the algorithmic modeling will be presented, accompanied by an extensive set of testing experiments, presented to determine the feasibility of our proposed developments in this field.

Keywords: robotics, navigational robots, trigonometric algorithm modeling.

INTRODUCTION

Robots development has met tremendous developments within the last years, as it can be seen in various papers Gupta *et al*. (2021), Lim *et al*. (2016), Kruse *et al*. (2013), Palamas and Ware (2013), Müller *et al*. (2004).

The logistics and planning of warehouse storage and transportation of stock is in a never-ending development. Modern companies have since the industrial revolution found out that optimization was a fundamental way to lower costs.

A new era of logistics has started, much more complex than people have experienced before. Previously, people would receive orders and walk to the location of that order for the specific object. Now, the objects are delivered to the person, this phenomenon being called "goods-to-person". Logistics automation (LA) is a commodity that companies are strongly focusing on, to make sure they are competitive in the market. LA is a way to improve the efficiency of the logistic operations within the warehouse or distribution centers. Optimization through innovation is a substantial part of the development happening in the field of logistics.

Replacement of employees by Automated Guided Vehicle (AGV) robots can cheapen the production costs and transfer the risk of work injuries on the shoulders of the robots – Balaji *et al*. (2022), Hasan *et al*. (2021). Employees in warehouses are instead allowed to focus more on management and planning, since the robots can lift, move and, in general, work faster and on heavier loads. However, more issues are to be considered when placing a robot in a warehouse.

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The challenge is to make the robot self-navigating, obstacle avoiding, and able to pick, plug, to move objects and so on. The AGVs must be able to know their own position, where they are heading and how they may get there.

To keep our research focused on the development of a functional AGV which may eliminate the costs of redesigning warehouses, the following problem statement has been defined: “How can one create an AGV utilizing an innovative indoor positioning and navigation system?” We have to mention that the present paper will not have in focus the design development of the chassis of the AGV

Using encoders to control the motors of the AGV should significantly improve the accuracy of the algorithm and reduce the number of triangles that need to be computed and analyzed in order to reach the final target point. A method of detecting obstacles has also been implemented.

HARDWARE DESCRIPTION

Our engineering research is focused on the creation, optimization and testing of an AGV with essential logistic functionality. In order to help develop ideas about already existing navigational robots, conducting an analysis on previous research is fundamental in our process. There are three very clear aspects which all previous researches agree to be needing taking into consideration: map building, path planning and obstacle avoidance – Michalson *et al*. (2012).

The robot hardware system is divided into three main parts, a communication and localization part, an obstacle avoidance part and a motor part. The robot is meant for indoor automatic navigation within warehouses, therefore appropriate hardware choices must be considered, making it a specialized unit which is considered to function optimally under the assumption of an indoor (low interference) setting.

Communication and Localization Part

The advancements of technology have recently allowed fast communication and data transmission to be carried out by wireless networks and services. One area of ICT in which radio waves are used very frequently and in which they are vital to the functionality of the embedded systems is within localization, mapping and positioning.

UWB (Ultra-Wideband) is a recently-emerged wireless technology that uses very low power of spectral density (~ 0.5 mW) and a high frequency range (known possible range: from 3.1 to 10.6 GHz) in order to achieve, among other uses, accurate positioning of robotic systems even in small rooms (because of its mean error range of 100 mm). Theoretically, only very little interference is possible even on already used frequency bands, due to it using less power than the background noise.

By using an anchor/tag combination of 4 UWB transceiver anchors (which have similar functionality as a satellite in a GPS system) across the warehouse room, the system is able to determine the location of the tag and identify its coordinates on a map with user-specified xOy axes. We implemented such a system of localization across our testing warehouse room environment, and the signal of our system allows very accurate timing measurements (0.16 µs), penetrating through 1 or 2 thick concrete walls, which is enough for most indoor room localization scenarios. The maximum range that it can achieve, based on tests, is 200 meters in clear line-of-sight.

Whereas this paper does not focus on the design engineering of mechanical parts for such a robot, an image of one of our developed AGV prototype is presented in Figure 1.

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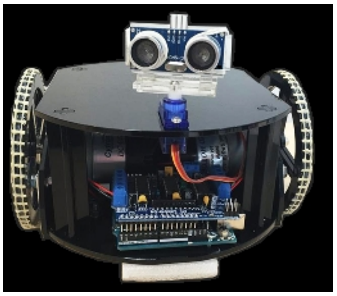

Figure 1. Prototype chassis and component representation of the AGV

Obstacle Avoidance Part

The obstacle avoidance sensor was selected to be able to detect objects in a cone field from a certain distance in front of the robot vehicle, ensuring that the robot would not collide with other objects. Furthermore, it is necessary to be able to measure distances, allowing the AGV to gradually move close to an object, and to function in various environments without disturbances from e.g. ambient light. The sensor should be kept lightweight for low weight, power consumption and cost. The Ultrasonic Rangefinder sensor (USS) works through an internal clock, taking the time between the sensor emitting and receiving the sound wave, giving the sensor a cone-like field of view. Through cross-implementation of such sensors, an even wider angle of detection could be achieved. However, using several ultrasonic sensors may cause interference problems, where one sensor catches the ping of another (referred to as “ghost echo”).

Motor Part

A lot of research went into finding a motor suitable for our case, in order to lower the risk of movement hardware failure. From investigations of other research involving driving AGV robots, three main types of motors have been identified as potentially suitable: DC motors, Servo motors and Stepper motors. On the background of the investigation of the different motors, we have selected a brushed DC motor equipped with an encoder as the optimal motor for this project, as it balances out hardware expenses with the ability to provide decent amount of power with good precision. Our small AGV prototype, presented in Figure 1, was able to achieve speeds of 250 mm/s using two brushed DC motors. For the motor specifications we chose to prioritize torque over RPM, keeping in mind that the robot was essentially meant to function in a warehouse environment. The high torque allows the robot to carry more weight.

UWB LOCATION AND COMMUNICATION – SYSTEM TESTING

In order to test the location of the robot across the warehouse floor, we have analyzed the movement and location patterns of the AGV in a 3500 mm x 4800 mm room, with the UWB anchors placed on each of the four corners of the room.

The robot would be found at coordinates notated in “*x*-mm, *y*-mm” measured from the anchor to the robot’s position. We have performed three different sets of tests, one where the UWB system would be in clear sight of all the other anchor transceivers.

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Then, separate test sets will be performed, where static and, respectively, dynamic interference would be added, due to both static and moving solid objects.

Testing without Interference

The first test only focused on the reliability of the UWB location. This means that there was no interference of any kind and the wireless tag was in clear sight of all the anchors. When examining the results from the system, it was clear that the found coordinates are really close to the true position, with only small differences (10-20 mm). This shows that the UWB positioning can be reliable if it is in clear sight of all the anchors. The second test was done in a similar way, modifying the number of calibrations and the original coordinates. We have noticed that the robot is found to be within 10-30 mm of its initial coordinates, showing that more static calibration measurements does not make the pinpointing more precise. Then, three more tests were executed without interference. The results are gathered in Table 1.

Table 1. Average UWB test results (without interference)

Number of samples	Number of calibrations	Original *x* coordinate (mm)	Original *y* coordinate (mm)	Average *x*-values (mm)	Average *y*-values (mm)	Average error *x* (mm)	Average error *y* (mm)
1	10	1000	1000	1018.37	1088.53	18.37	-11.47
1	30	900	900	912.74	931.47	12.74	31.47
10	10	1000	1000	978.81	961.19	-21.19	-38.81
10	30	1000	1000	1010.94	976.33	10.94	-23.67
10	30	1000	2000	1027.86	2060.86	27.86	60.86

Testing with Static Interference

Afterwards, we have chosen to test the same AGV system with introducing static interference, to get a more realistic view on how the UWB would behave in an environment where interference can happen, such as a warehouse. This was verified through a set of two more tests, in which we placed a static object between the robot and the axis. We note that interference has a tremendous impact on the results, leading to positioning errors of up to 200 mm. The errors are also very different depending on which location anchor is the one being interfered with. It appears that the coordinate attribute of the anchor that is having its signal interfered is pushing the axis coordinate location estimate further away from the original coordinate. The results are presented in Table 2.

Table 2. Average UWB test results (with static interference)

Number of samples	Number of calibrations	Original *x* coordinate (mm)	Original *y* coordinate (mm)	Average *x*-values (mm)	Average *y*-values (mm)	Average error *x* (mm)	Average error *y* (mm)	Inter-ference axis
10	30	1000	2000	981.67	2105.83	-18.33	105.83	*x*
10	30	1000	2000	1206.44	1821.44	206.44	-178.56	*y*

Testing with Random Dynamic Interference

The last executed test was performed in a moving state of the robot, while the AGV was moving along the y-axis following a linear path, keeping the same x-coordinate constant.

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The wireless environment had been naturally polluted by signals of various electronic equipment, just as it would be in an actual warehouse setting. Then, we are performing a signal reliability test, in which we are interested only in computing the x-coordinate of the AGV, since the robot should be keeping the x-coordinate constantly close to its original value, while moving on the *y*-axis. The results are shown in Table 3.

Table 3. Average UWB test results (with random dynamic interference)

Number of samples	Number of calibrations	Original *x* coordinate (mm)	Average *x*-values (mm)	Average error *x* (mm)	Free moving axis	Interval of movement (mm)
10	30	1590	1580.38	-9.62	*y*	0 - 3000

We can conclude that, even though the UWB location system produces errors regardless of the presence of interference or not, the error found due to static interference may sometimes be substantial. Therefore, it must be made sure that all the UWB anchors are in clear sight of the tag on the robot, otherwise it will not be able to maneuver accurately enough.

ULTRASONIC RANGEFINDER SENSOR – OBJECT DETECTION TESTING

In order to investigate the behavior and reliability of the USS obstacle detection sensor, a total of six tests were carried out, each measuring a different property of the sensor. The tests were conducted by setting up various real floorplan scenarios that the robot could encounter, so that we measure the most accurate responses of the sensor in various conditions.

The following types of tests were conducted: code testing; accuracy of length measurements; objects' material response; angle measurements; "ghost echo" test and also height test. For all of these tests, the USS was mounted on a box to simulate the height it would have had if it was mounted on the robot, since, when this testing was performed, several parts of the actual robot were not yet manufactured, thus requiring us to get a static estimate of the sensor's performance. Since each test is rather long in description of data and execution, we will present the aggregate insights which have been found about the USS sensor below. We have determined that taking an average of 5 sensor readings per obstacle distance measurement best produces a balance between speed of computation and accuracy of the measurements.

Regarding the accuracy on different types of object materials, various types of wood objects have yielded no change in measurement error, regardless of their different wood properties. When testing on a porous object (a blackboard sponge), it could be seen that the sponge absorbs some energy of the sound waves, as the measurement readings were largely inconsistent, therefore this test determined that the USS would not allow the AGV to avoid obstacles made of materials which can absorb a large amount of sound wave energy.

For this sensor, we have determined the angle of the sensor's field of view to be 30° for objects detected at 300 mm or more from the sensor. When trying to detect object in very close proximity of the sensor (100 mm or less), the field of view drops to below 15°, however we could assume that the robot would not approach objects this close without first identifying them from further away. For short-sight collisions, the sensor is reliable for scenarios where an object is placed in its straight line-of-sight.

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CONCLUSIONS

The present paper has described an optimized Automated Guided Vehicle (AGV) which can efficiently navigate a warehouse floor plan using a combination of indoor, ultra-wideband wireless positioning sensors, and ultrasonic sensors for obstacle distance measurement and avoidance.

Using the method of wireless energy wave multilateration, this paper has proven that ultra-wideband technology may be used in future indoor robot navigation endeavors, however, as it can be seen from our tests, it must be mentioned that this method does suffer from high sensitivity to signal blocking and static interference.

On the other hand, the system has proven to be very stable to dynamic interference and wireless signal pollution.

The Ultrasonic Rangefinder sensor has proven to be an accurate choice for obstacle detection and avoidance within a cone field-of-view in front of the robot, however point-blank collisions could be detected even at small distances.

Whereas our prototype has only been using one of such USS sensors, we argue that a larger, multilateral field-of-view detection of obstacles can be achieved by utilizing an array of such sensors.

However, as we have discovered, such implementations will have to deal with the capturing of ultrasonic signal echo from one USS to another close-by USS within this sensor array, thereby requiring mitigation of this problem, known as "ghost echo".

Accurate indoor positioning sensors are at its early stages of development, however, with more research done into the algorithmic modeling area of localization, we can expect that wireless sensors will be in the forefront of providing the necessary hardware considerations of allowing high positioning accuracy in otherwise difficult-to-achieve scenarios.

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