

Article

Survival 1.0: A Novel Autonomous Industrial Mobile Warehouse (AIMW) for Industrial Environments

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Abstract: This article presents the design, implementation and start-up of the first AIMW (Autonomous Industrial Mobile Warehouse) in the industry, in particular, in the factory located at Ford España S.L. in Almussafes (Valencia). This first version has been given the name of “Survival”, due to its ability to survive the industrial environment commonly known as “the jungle”. The motivation for the design of the first AIMW was due to the management of spare warehouses for maintenance tasks. In all factories there is a central warehouse where replacement materials with a higher probability of use are placed near the warehouse exit, thus reducing the time to obtain the replacement. However, in large factories, such as automobile manufacturing, the distance between the central warehouse and the place where the breakdown occurs may cause very long delays. For this reason, there are smaller warehouses distributed throughout the plant that replicate the part of the central warehouse where the most used materials are kept. The objective of our research is to make that part of the central warehouse mobile with the AIMW design, thus eliminating the fixed warehouses. In the factory at Ford España S.L. in Almussafes there are 170 of these warehouses distributed in a homogeneous way. In this first proposal of an AIMW, and with the primary objective of reducing costs, Survival 1.0 has been designed based on a commercial AMR. For its choice, commercial AMRs were tested in real situations within the Ford factory (Almussafes). As a result, none of them were able to pass all the tests. In addition, the current regulations for AMRs, the ANSI/ITSDF B56.5:2019 and the EN 1525:1997 standard, only define minimum test standards to describe how manufacturers and users must carry out the safety measurements of AGVs and AMRs. However, from an industry point of view, these regulations are not adequate. Therefore, there are extensions of these regulations generated by the companies themselves that imply additional developments of commercial AMRs. This paper shows the developments made to be able to integrate the first AIMW into the production line, but it also shows the gap between research and standardization of AMRs with respect to the demands and needs of the industry. There are currently three Survival 1.0 AIMWs in operation in the factory at Ford España S.L. in Almussafes.

Keywords: AGV; AMR; AIMW; industrial environment



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1. Introduction

The production flow in manufacturing plants has been deeply automated in recent decades in order to reduce costs and avoid unsafe working conditions. Manufacturing plants often need warehouses for raw materials and final products at the beginning and end of the production line. Despite the automation of production, logistics is still poorly automated and still requires manual operations performed by human workers. Therefore, logistics is not fully integrated into manufacturing processes and leads to inefficiencies along with high-risk working conditions for workers [1]. Factory logistics is crucial to

the overall production flow and its weakness may affect production efficiency, generating bottlenecks and the quality of goods delivery, especially in terms of product traceability.

Modern logistics warehouses and distribution centres are designed on the basis of dozens of optimization studies. As a consequence of this, warehouse management systems (WMSs) have increased in importance but also in complexity, which makes them quite difficult for users to manage, especially for dynamically changing tasks over time, see [2].

1.1. Management of Spare Parts Warehouses for Maintenance Operations

In factories, there are not only warehouses with raw materials or manufactured products, there are also warehouses with spare materials for use in maintenance tasks. Management of the latter is not as complex as other warehouses since the tasks do not change over time. In this case, the replacement materials with a higher probability of use are placed near the warehouse exit, thus reducing the time to obtain the replacement parts. However, in large factories, such as automobile manufacturing, the distance between the central warehouse and the place where the breakdown occurs can cause very long delays. For this reason, there are smaller warehouses located throughout the plant, containing the most common materials needed to perform typical repair tasks. If we take into account the materials that are placed at the exit of the central warehouse as an independent warehouse, what is being done is to replicate this smaller warehouse with the most typical materials throughout the factory to minimize access times to the necessary materials and, therefore, minimize the time to repair the fault.

At Ford's factory in Almussafes (Valencia) there are 170 of these warehouses distributed throughout the plant, see Figure 1. The materials contained in these warehouses are basically the same: capsules, clamps, fittings, gloves, photocells, detectors, etc. The difference between them is marked by whether there is any line that instead of having a photocell A has a B one due to its characteristics, although the objective of the factory is to standardize them and make them the same.



Figure 1. Cabinets with most common spare parts.

The distribution of these cabinets is regular throughout the facilities, allowing the maintenance and production operator to have access to spares near the manufacturing line and thus reduce the repair time of the fault, which is defined as the MTTR (Mean Time To Repair). For this spare parts maintenance system, it is necessary for some storekeepers to go through the pre-established routes, deliver the required materials in each area when they are not stored in the cabinet or are simply not found among the common parts, and obtain the data of the requested materials using a barcode reading system to minimize human error.

The spare parts delivered to the different facilities are small in size and are distributed according to the name of each MWG (Manufacturing Work Group), that is, the manufactur-

ing line, see Figure 2. Although a barcode is used to try to minimize human error, during the process of distribution of spare parts by the operator, confusion and errors often occur that make the distribution system inefficient.



Figure 2. System for distribution of materials.

Currently, there is a recent trend towards robotic and human collaboration [3,4]. This trend is closely related to Industry 4.0 and, more generally, to IIoT concepts. It has been fuelled by recent developments in the world of Information Technology and industrial electronics or even materials science. Enabling technologies for these trends are, e.g., smart sensors [5] for a better perception of a robot's environment, and industrial communications [6,7] for improved real-time interaction and coordination not only among robots but also between them and their environment. In this context, wireless communications have played a decisive role, since they support the mobility of robots, as well as the inclusion of sensors or actuators around the real robot [7].

1.2. Autonomous Mobile Robot (AMR) vs. Automated Guided Vehicle (AGV)

The first known automated guided vehicle (AGV) was introduced by Barret Electronics of Northbrook, Illinois, USA, in 1953 [8]. However, its appearance in the industry in a massive way began a little over a decade ago, driven by the advances introduced in the fourth industrial revolution.

One of the essential initial premises is to understand the difference between an Autonomous Mobile Robot (AMR) and an automated guided vehicle (AGV) [9,10].

An AGV has minimal on-board intelligence and can only obey simple programming instructions. To navigate, it must be guided by cables, magnetic strips or sensors such as RFID (Radio Frequency Identification) [11], which generally require the installation of extensive (and expensive) facility upgrades, during which production may be disrupted [12]. The AGV is restricted to fixed routes, which require additional cost and interruption if changes are needed in the future. The AGV can detect obstacles in front of it, but cannot navigate around them, so it simply stops short until the obstacle is removed [10].

On the contrary, the AMR navigates through maps built through a learning process, which consists of scanning the environment by using sensors or through previously drawn maps that represent the environment of the facility [12]. This ability can be compared to a car with a GPS and a set of pre-loaded maps. When it is shown the address of the owner's home and work, it generates the most direct route based on simple positions on the map [10]. This is similar to the way the AMR is taught to find out the location to pick and drop the parts. The AMR uses data from cameras, built-in sensors and laser scanners, as well as sophisticated software that allows it to detect its environment and choose the most efficient route to the target. It works completely autonomously, and when forklifts, pallets, people or other obstacles are in front of it, the AMR will safely manoeuvre around

them, using the best alternative route. This optimizes productivity by ensuring material flow remains on schedule [10].

AMRs are often used for material handling. They are usually designed in the form of robot arms or actuators built on mobile platforms [12]. AGVs, on the other hand, are most often used in industrial applications to move materials around the manufacturing line or in a warehouse [4,12]. In some cases, an AMR can be built with an AGV that is used as a mobile base to achieve the stated objectives [13,14].

Currently, research on AGVs and AMRs has become a topic, motivated mainly by the rise of Industry 4.0 technologies and by the fierce competitiveness of companies. In the case of AGVs, research is continuing to improve these systems, especially when there are multiple AGVs sharing the same routes, see [15], and research is being carried out to increase their capabilities and transform them into Smart AGVs that can interact with humans, see [16]. In the case of AMRs, one of the main lines of research is to make them more robust for industrial environments in the process of autonomous navigation, continuous self-location and representation of the goal [17]. In [9], they try to optimize the behaviour of AMRs in industry through the “Highway code” concept. The idea is the generation of high-level rules that manage AMRs, in a first version, in simulation environments.

One of the applications that AMRs have in the industry is found in what is known as Industry 4.0 warehouses, smart warehouses [18]. In this research, we work on how to optimize the automatic management of warehouses through the AMRs and how they interact with each other, etc. In general, the industrial solutions, see [19], usually involve programming an AMR to carry a shelf or cabinets where operators place the goods and then send them to another site, see Figure 3. These robots are prepared to work in controlled environments rather than in industrial environments such as factories.



Figure 3. Different AMR warehouses of the Zebra brand found in the market, obtained from [19].

1.3. Autonomous Mobile Robots for Specific Applications

In most modern applications, both AMRs and AGVs are used interchangeably to refer to autonomous devices that can perform industrial tasks [20], which can include material handling, research activities, collaborative work with humans (cobots) or cooperative activities with another AGV or AMR [12].

One of the applications of AMRs can be the manipulation of materials through a robot arm or actuator located on it. These types of devices are known as Autonomous Industrial Mobile Manipulators (AIMMs) [21,22]. The great advantage these systems offer is that they can be quickly moved and adapted to different industrial needs, providing drastically new possibilities for manufacturing industries. Unlike traditional, stationary and pre-programmed production robots, AIMMs can support multiple locations. They are able to offer highly flexible logistical possibilities and can improve productivity by providing assistance in situations that require a lot of time, danger or stress [23]. In AIMMs, the rover base and robotic arm can be considered as separate subsystems that collectively are part of a complex AMR. The base, which can be an AGV, is often used to transport, dock or park the

robotic arm in a location where the arm is needed to perform a specific task [20]. Research is currently being carried out on how to improve these platforms. In [24], a new platform called Omnivil has been proposed, in which the main novelty is the monitoring of the work environment to improve robot–human interactions. In [25], the collaborative interaction among AIMM platforms, known as Collaborative Mobile Industrial Manipulator (CMIM), is being researched. There is also research on the development of these types of platforms for different applications. For example, in [26], a platform called KittingBot has been proposed for use in kitting tasks, basically in automobile manufacturing.

Recent research has focused on developing other types of specific applications through the use of commercial AMRs, see [27,28]. In [27], a mobile robot called Phollower was designed and equipped with the latest types of industrial components and sensors. The robot is equipped with a germicidal UV-C light add-on for disinfection of indoor areas. In [28], a MiR100 mobile robot platform is used to cooperate with the production line, take over the manufactured products and then deliver them. Regarding the use of commercial hardware, in [27] a Programmable Logic Controller (PLC) and open-Powerlink communication are used and in [28] a MiR100 mobile robot platform, (manufactured by MiR, Odense, Denmark) is used, which allow the expansion of these types of new applications to be easily extensible and generalizable, that is, become industrializable because the components are known and there are personnel trained in their handling and problem solving, etc. This new trend in research is in line with what was developed in our previous work regarding the development of industrializable IIoT applications, the I3oT (Industrializable Industrial Internet of Things). In this case, we intend to use what is already installed in the factory for the development of applications that allow to improve the production lines, see [29,30], developing applications that are easy to mass produce and generalize.

2. Objective of Our Line of Research

What was proposed in our previous works, the I3oT (Industrializable Industrial Internet of Things) [29,30], as well as the developments of [27,28], open a new line of research that seeks to propose improvements for industry that are industrializable, so that the industry can absorb them and make the change from Industry 4.0 to Industry 5.0, something that will not happen as long as the emerging technologies of Industry 4.0 are not mass produced and widespread in the industry. The objective of the present article is to show how to develop an Autonomous Mobile Robot for a particular application, in this case a mobile warehouse, Autonomous Industrial Mobile Warehouse (AIMW), using commercial components to improve its industrialization. The idea, like the one used to develop AIMMs, and [27,28], is to use a commercial AMR as a base to build a more complex AMR on it, which in our case consists of an intelligent warehouse, managed by a PLC and commercial communication protocols, which allows to be made mobile the part of the central warehouse that is closest to the exit that contains the most common spare parts, in order to eliminate the replicas distributed throughout the factory.

This type of autonomous robot has been given the name “Survival”, due to its ability to survive the industrial environment commonly known as “the jungle”. This article shows the design and implementation of the first version of Survival, Survival 1.0. In this first version, and with the primary objective of reducing costs, the AIMW has been designed based on a commercial AMR, managed by a PLC and commercial communication protocols, and the size of the smart warehouse has been adjusted to the manufacturer’s restrictions. Section 3 shows the AIMW design, from the AMR choice, smart warehouse design and adaptations necessary to meet Ford’s internal regulations and standards. Section 4 shows how Survival 1.0 works. A discussion about the development of this type of mobile robot in the industry and the achievement of our objective can be found in Section 5. The conclusions and future work can be seen in Section 6.

3. Design of the First Autonomous Industrial Mobile Warehouse (AIMW)—Survival 1.0

One of the premises when designing industrial applications is the quality vs. cost ratio. Following the AIMM design philosophy, when coupling an AMR with a robot arm, the inexpensive way to design an AIMW would be to couple a commercial AMR with the smart warehouse. Therefore, when designing Survival version 1.0, the first step was to choose the commercial AMR.

3.1. Choosing the Commercial Autonomous Mobile Robot (AMR)

After a first estimate, it was considered that the weight that the AMR was going to support, including the weight of the material and the warehouse itself, would be 75–100 kg. Therefore, we sought AMRs with these characteristics in the market. The following table shows the models found with this restriction and their technical characteristics. The AMRs found on the market that meet the specifications belong to the companies OMRON, see [31], MIR, see [32], and ROBOTNIK, see [33].

As seen in Table 1, there are no significant differences among the existing AMRs on the market, from the point of view of their technical specifications. They are all capable of building maps and self-locating, and they have the usual inputs/outputs, Wi-Fi, Bluetooth, etc.

Table 1. Technical specifications of existing AMRs on the market.

	Omron MC105	Omron MC130	MIR 100	RB-XL Steel	RB-Sherpa	RB-2
Mechanical specifications						
Sizing (mm)	1020 × 894 × 1398	1020 × 894 × 1398	900 × 600 × 358	699 × 515 × 415	1142 × 1413 × 626	736 × 595 × 350
Weight (unloaded)	79 kg	79 kg	62.5 kg	90 kg	123 kg	75 kg
Load Capacity	105 kg	130 kg	100 kg	130 kg	100 kg	200 kg
Ground Clearance	-	-	50 mm	163 mm	234 mm	-
Max. Speed	1.35 m/s	0.9 m/s	1.5 m/s	3 m/s	3 m/s	1.7 m/s
Max. Slope	5%	5%	5%	30%	30%	-
Ambient Temperature Range	-	-	+5 °C a 50 °C	+0 °C a 50 °C	−10 °C a 45 °C	
Personalisation	No	No	Yes	Yes	Yes	Yes
Wheel Strength	Medium-Low	Medium-Low	Medium-Low	High	High	-
Movement	Unid.	Unid.	Unid.	Multid.	Multid.	Multid.
Navigation						
Area Mapping	Yes	Yes	Yes	Yes	Yes	Yes
Trajectory Recalculation	Yes	Yes	Yes	Yes	Yes	Yes
Route Modification	Yes	Yes	Yes	Yes	Yes	Yes
Speed According to Zone	Yes	Yes	Yes	Yes	Yes	Yes
Communication						
WiFi	802.11 a/b/g	802.11 a/b/g	Dual Band	802.11n	802.11n	
Bluetooth	-	-	Si	?	?	
S.O.	-	-	ROS	ROS (Pc Linux)	ROS (Pc Linux)	
USB	Yes	Yes	Yes	Yes	Yes	
Ethernet	Yes	Yes	Yes	Yes	Yes	
RS232	Yes	Yes	-	Yes	Yes	
Digital I/O	Si	-	-	-	-	
Position Monitoring	Yes	Yes	Yes	Yes	Yes	
Status Monitoring	Yes	Yes	Yes	Yes	Yes	
Safety						
IP	-	-	20	54/65	54/65	54

Therefore, in order to choose the most appropriate one, we had to test them in industrial conditions and determine which was the best in this type of space. The tests carried out were the following:

- Test 1—Obstacles in different positions: In this test, objects are placed at different heights and positions (within the range established by the manufacturer for the load to be transported).
- Test 2—Non-solid objects: This test is particularly focused on determining the detection capacity of the cages of industrial robots.
- Test 3—Cornering: In this test, the aim is to determine the ability of the AMR to find alternative routes to avoid a possible cornering by several operators.
- Test 4—Industrial vehicles: This test seeks to determine the ability of the AMR to detect industrial vehicles of different sizes, with different wheels and colours.

Table 2 shows the test results and whether or not the AMRs passed them successfully.

Table 2. Results of the tests performed on the AMRs.

	Omron MC105	Omron MC130	MIR 100	RB-XL Steel	RB-Sherpa	RB-2
Test 1	NO	NO	NO	NO	NO	NO
Test 2	NO	NO	YES	NO	NO	NO
Test 3	YES	YES	YES	YES	YES	YES
Test 4	YES	YES	YES	YES	YES	YES

As seen in Table 2, none of the AMRs are capable of performing satisfactorily in industrial environments. There are two big problems. The first is the detection of obstacles in different positions, since commercial AMRs have blind spots of vision that could cause collisions with the load within their range of motion. The other problem is the AMRs' ability to recognize non-solid structures as obstacles. In this case, the main drawback is the cages of the robot arms. The only AMR that is capable of recognizing robot cages as part of the layout is the MIR 100.

Therefore, the MIR 100 was selected as the AMR on which the AIMW will be built. As MIR robots are standard, the company that manufactures them has not changed their CE marking, so it was necessary to install an additional scanner at a certain height. In Survival 1.0, a SICK sensor was installed at 1 metre from the ground, see Figure 4. In order not to lose the CE marking of the MIR 100, the SICK sensor was connected in series to the external safety connector of the MIR 100.



Figure 4. Additional sensor to avoid collisions with objects in different positions.

3.2. Smart Warehouse Design

The first step in the design of the smart warehouse was its size. For this, the restrictions of the manufacturer of the MIR 100 had to be taken into account. In this case, the maximum height recommended by the manufacturer was 1800 mm from the ground, where the centre of gravity must always be below 900 mm. The second step was the design and sizing of the boxes. For this, the typical material that the warehouse had to transport was analysed. As a result, 17 boxes of different sizes were arranged as shown in Figure 5.



Figure 5. Smart warehouse design.

The boxes have a gate that can only be opened by the PLC managed by the AIMW. Therefore, when Survival 1.0. reaches its destination, the operators can only access their own boxes.

3.3. Standardization and Regulations

Automatic Guided Vehicles (AGVs) have been commonly used for industrial material handling since the 1950s. Since then, the safety standards of the U.S. in 2021 and Europe in 1998, for AGVs and AMRs have evolved to protect the workers around them. Currently, the regulations in force are the ANSI/ITSDF B56.5:2019 standard [34] and the EN 1525:1997 standard [35]. These standards have minimal test methods to describe how manufacturers and users should perform safety measurements for the AGVs and AMRs, resulting in possible differences depending on the users' requirements [36]. For this reason, companies often develop complementary specifications to the standard and thus increase the level of security for these types of devices. For example, Ford S.A. has the standard w-ZA65 7.5 [37]. This internal standard adds the light indicators of vehicle status and direction of movement to the ANSI/ITSDF B56.5:2019 and the EN 1525:1997 standards, see Table 3. In addition, to ensure that the robot is seen by each person or vehicle in its environment, two devices must be incorporated, see Figure 6, which are:

- Sound beacon: emits an intermittent acoustic signal to warn of the robot arrival in the surroundings (10 dB above ambient sound).
- Strobe flash light installed on a tall pole: allows the robot to be seen from above the obstacles.

These elements are activated when the robot is performing the process of the materials delivery. Both the sound beacon and the strobe light allow operators to know that the robot is approaching, to avoid collisions at corners or intersections. Lastly, the w-ZA65 7.5 standard requires an emergency stop button. Although the MIR 100 has already incorporated it to comply with the ANSI/ITSDF B56.5:2019 and EN 1525:1997 regulations, the w-ZA65 7.5 regulation requires an additional button that includes the automated parts, in this case, the parts of the smart warehouse.

Table 3. Additional requirements of the beacon light in the standard Ford w-ZA65 7.5.

Colour	Description
Green (steady)	Vehicle in automatic
Flashing green (80–90 FPM)	Indicates that the vehicle is moving or can move at any time automatically
Red	The vehicle is at a programmed stop station and connected to a charger
Flashing red (80–90 FPM)	Vehicle is in a fault condition
Blue	The vehicle is in stop condition and needs a release signal to start
Flashing amber (80–90 FPM)	Indicates in advance a turn to be made by the vehicle
White	The vehicle must provide a visual and/or audible indication of a low battery condition

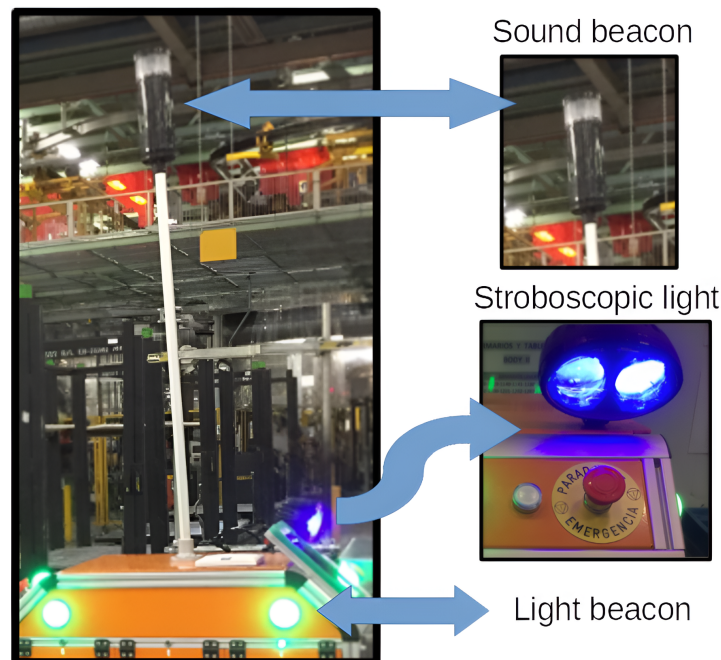


Figure 6. Additional safety elements of Ford regulation w-ZA65 7.5.

3.4. AIMW Control System

The AIMW, made up of the smart warehouse and the AMR MIR 100, is controlled by a PLC that manages the entire system, see Figure 7. The AMR communicates with the PLC through a serial port, allowing the PLC in charge of warehouse management to indicate the elements that it must manage in each defined position of the AMR within the map; these elements are the box doors, the lighting elements, audible beacon, stroboscopic light

and safety elements necessary to comply with the regulations, see Section 3.3. It also has a wirelessly connected tablet to receive instructions and a GPRS modem to send messages to those responsible for unloading the robot.

To interact with the AIMW, there is an HMI (Human Machine Interface), see Figure 8, where the following operations are performed:

- Cabinet door opening control.
- Assignment of slots to each delivery point.
- Materials collection confirmation.
- Materials collection check at the end of delivery.
- Bar code reading control process performed by the user.
- HMI (Human Machine Interface) to interact with the AIMW.

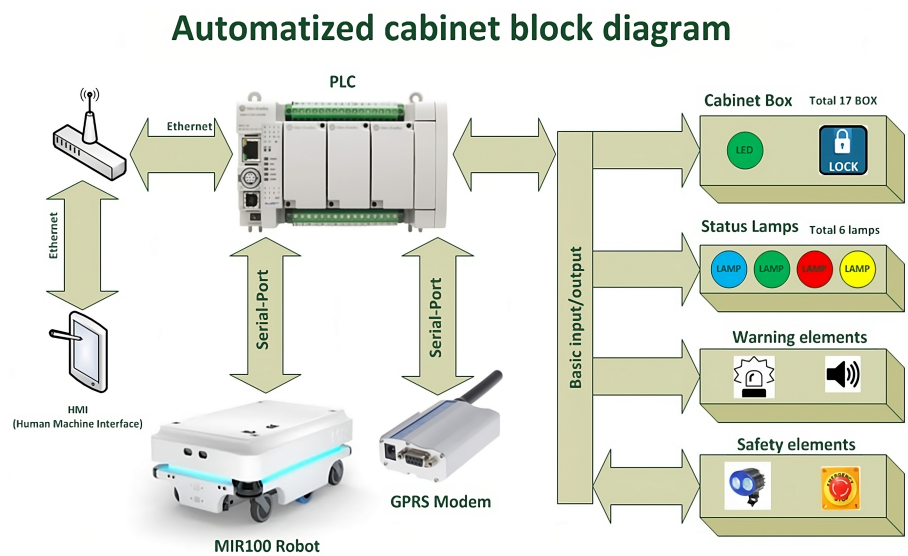


Figure 7. Hardware control system.

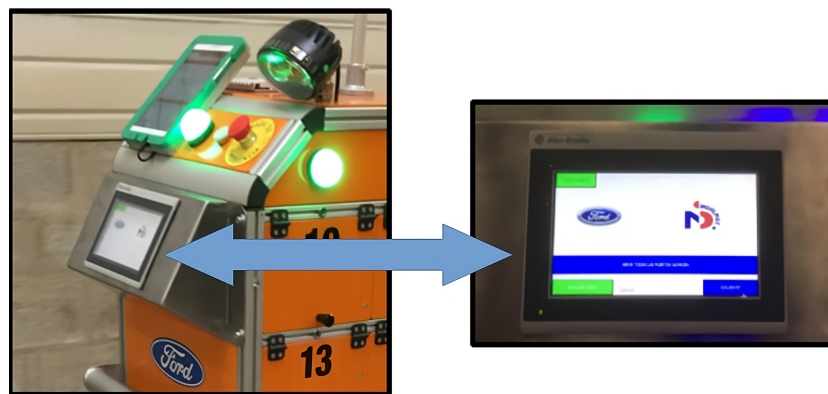


Figure 8. HMI (Human Machine Interface) to interact with the AIMW.

4. Operating Mode

The way the AIMW works with the different operators can be seen in Figure 9. The operations to be performed in the central warehouse are the following:

1. Choose the destination.
2. Assign box/destination.
3. Start route.

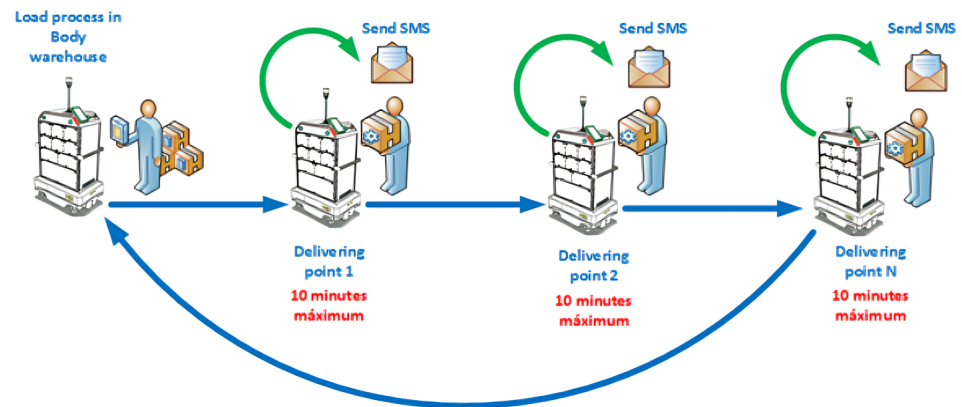


Figure 9. Survival 1.0 operating mode.

The operator selects the destination of the predefined points on each floor, see Figure 10, assigning the box where the material will be placed. The operations to be performed by the AIMW are:

1. Optimize and navigate optimally between the different destinations.
2. Send an SMS to the assigned operator when arriving at the destination.
3. Wait for the operator to collect the material (only the corresponding box is opened).
4. If there is no confirmation in 10 min, the AIMW continues to the next destination.

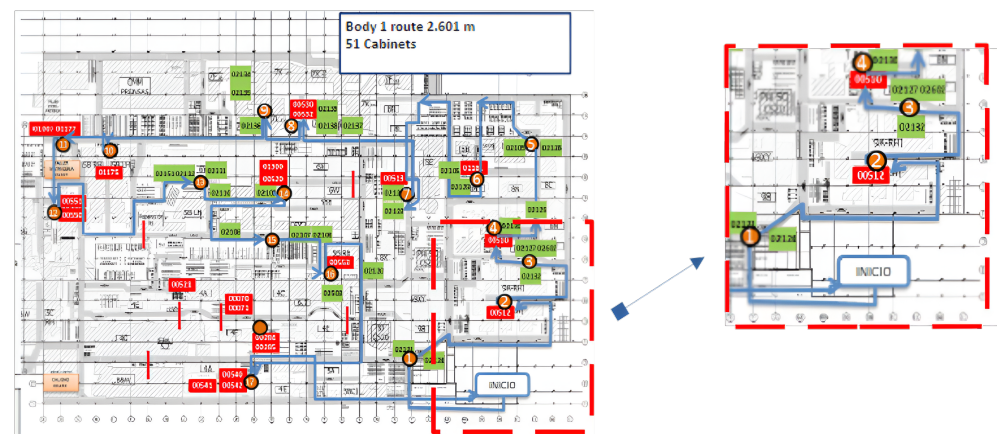


Figure 10. Predefined routes.

The operations to be performed by the recipient of the material are:

1. Receive the SMS.
2. Go to the collection point and locate the corresponding box.
3. Press the open button of the box.
4. Pick up the material.
5. Press materials collection confirmation.

The AMR MIR 100 is capable of building and navigating the map (SLAM), and therefore you only need to indicate the destination, which is marked by the coordinates of the collection points previously programmed on the map. The MIR 100 is responsible for optimizing the route and reaching the destination. Figure 11 shows maps built by the MIR 100 and destinations marked on its map (red dots). Figure 12 shows Survival 1.0 on one of its missions. In this image you can see the interaction with other vehicles and the effect of the strobe light indicating the direction of movement.

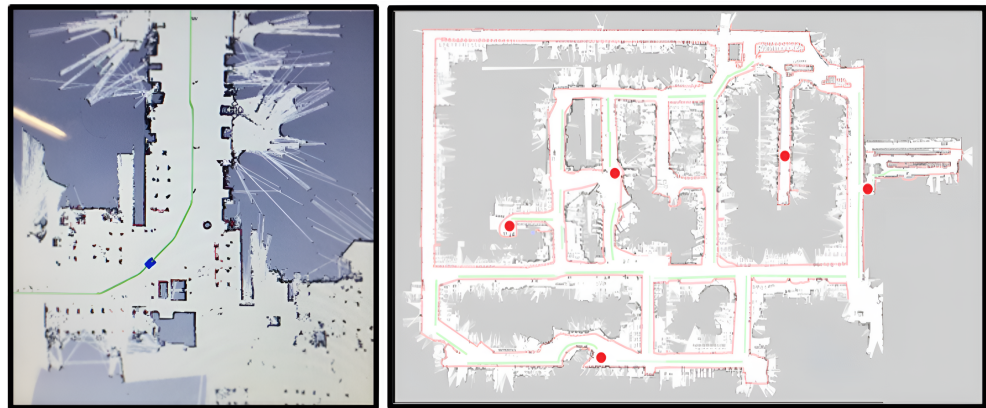


Figure 11. Maps built by the MIR 100 and destinations (red dots).

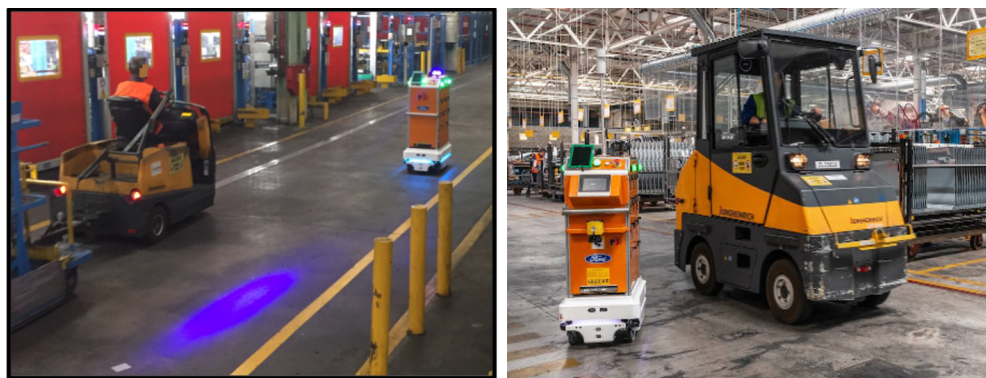


Figure 12. Survival 1.0 in one of its missions.

Currently, there are three Survival 1.0 AIMWs fully operating at the Ford plant in Valencia, which have been in operation for two years, see Figure 13. Since its launch, there have been no serious incidents and therefore we did not need to redesign the AIMW.



Figure 13. The three Survival 1.0 AIMWs at the Ford plant.

Improvements Achieved in the Factory

By automating this process, we have been able to balance the load of warehouse workers with two great benefits:

1. Delivery of materials in the central warehouse: Table 4 shows the breakdown of hours by plant (Body1, Body2, Body3, Stamping). Taking into account a year with 220 working days, the saving in labour is around two workers per year (1.88).
2. Distribution of employee clothing: Table 5 shows the breakdown of hours by areas (Body Shop, Warehouse & Tooling, Laboratory, Press Shop). Taking into account a year with 220 working days, the saving in labour is around three workers per year (2.87). This saving can be divided into two areas:
 - (a) The cabinets with materials have high turnover spare parts: two operators a day are dedicated to touring the plant cabinets with an industrial vehicle, reading the requirements with a barcode gun and delivering those already prepared in the warehouse.
 - (b) Supplies: each worker brings the dirty laundry to a fixed point in their MWG (Maintenance Work Group). A housekeeper picks up all the clothes and transports them in an industrial vehicle to the wardrobe warehouse of the body and stamping plant. Three operators are involved in the process every day.

Table 4. Hours saved in manual material delivery process at central warehouse.

	Body1	Body2	Body3	Stamping
Preparation (Warehouse)	0.75	0.58	0.42	0.42
Delivery Route	0.58	0.37	0.48	0.42
Reading and Delivery (Warehouse)	3.87	2.67	2.47	1.58
Number of Cabinets	51	40	37	21
Total Time (Hours/day)	5.20	3.62	3.37	2.42
Total Time (Hours/year)	1144.00	795.67	740.67	531.67

Table 5. Hours saved in manual material delivery process at central warehouse.

	Body Shop	Warehouse & Tooling	Laboratory	Press Shop
Invested time in collection process	387.00	306.00	291.00	351.00
Total Time (Hours/day)	6.45	5.10	4.85	5.85
Total Time (Hours/year)	1419.00	1122.00	1067.00	1287.00

5. Discussion

AMRs at an industrial level are still far from being ad hoc devices that a company can buy and use in its industry, and thus a gap remains between research and standardization of AMRs with respect to the demands and needs of the industry. In this article, we present the design of the first version of what has been called an AIMW, a smart warehouse on top of a commercial AMR. When trying to choose the commercial AMR, all those existing on the market, from the point of view of the technical sheet, offer similar characteristics but, when subjected to real situations in the industry, none of them are capable of satisfactorily solving the totality of scenarios that could be found. This has forced the industry to improve the AMR for the specific situations detected. Commercial AMRs are not prepared for this type of CE extensions or modifications, so if the industry wants to use commercial AMRs to develop more complex AMRs, it must find a way to do so without losing its CE marking.

The regulations that currently govern AMRs in the industry are another handicap to overcome in order to achieve the implementation of these devices in the industry. The

current regulations, ANSI/ITSDF B56.5:2019 and EN 1525:1997, only provide the necessary minimum standards. This forces companies to develop their own extensions in order to achieve an adequate level of safety. The number of AIMWs used is related to the size of the plant and the frequency of product demand. The three AIMWs described in this article have succeeded in replacing the operators.

6. Conclusions and Further Developments

This work shows the design, development and start-up of the first AIMW (Autonomous Industrial Mobile Warehouse), called Survival 1.0. The design of this first version has been restricted by the use of a commercial AMR, which has lowered the cost, but has also led to other drawbacks such as the need to add sensors to alleviate its deficiencies in navigation in industrial environments and the need to add elements to alleviate the lax existing regulations on these types of components, which forces the industry to generate its own standards.

The AIMWs presented in this article are a first step towards the development of more advanced AIMWs to replace the fixed warehouses distributed throughout the entire factory. This would allow the smart warehouses to be located in the places where the breakdowns occur. This line of research is linked to Industry 4.0 and the Miniterm 4.0 real-time machine failure detection tool, which is capable of detecting when a machine begins to deteriorate, see [38]. When the Miniterm 4.0 system detects a need for maintenance, this system sends a repair order to the maintenance operator to carry out the repair, but it also sends the AIMW with the necessary materials for the repair to the place where the failure occurs, so that the operator can obtain the available materials quickly and in the right place.

The proposed solution can be perfectly integrated with the rest of Industry 4.0 technologies, machine learning, IoT-based optimization, etc., to improve the management of this system, this being one of our future works.

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