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Mechanical and safety aspects of designing Autonomous mobile robot AMR for industrial applications

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Abstract:

Mobile robots are a response to the growing market demand for the automation of in-house logistics in order to achieve significant savings in personnel costs and higher efficiency in the area of intralogistics.

This article presents the design issues of the AMR autonomous forklift, with particular emphasis on mechanical and safety aspects. The process of selecting the chassis geometry and its impact on the dynamic characteristics of the vehicle and the design of safety zones are discussed.

Keywords: AMR, AGV, Autonomous mobile robots, intralogistics automation, industrial automation

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1. Introduction

As part of the Regional Operational Programme for the Małopolska Region for 2014–2020, Pro-Assem carried out a project involving R&D work, which resulted in the creation of a prototype of an autonomous mobile robot equipped with a lift or pick-up device. The prototype became the basis for implementing the results of the work into the activities of PRO-ASSEM Sp. z o.o. and for starting the production of autonomous robots.

This innovative project was a response to the growing market demand for the automation of internal logistics in order to achieve significant savings in personnel costs and higher efficiency in the area of intralogistics.

Autonomous mobile robots (AMRs) are gaining importance in modern industry. The history of unmanned vehicles in industrial applications dates back to the 1960s, when Barrett Electronics created the Guide-O-Matic self-propelled towing machine (Trebilcock, 2010). However, the real boom in autonomous industrial vehicles began in the 2020s (Straits Research, 2025), driven by the development of technologies enabling autonomy with limited or no need to modify factory infrastructure.

This article presents the design issues of the AMR autonomous forklift, with particular emphasis on mechanical and safety aspects. The process of selecting the chassis geometry and its impact on the dynamic characteristics of the vehicle and the design of safety zones are discussed.

2. Our Robot

AMR (Autonomous Mobile Robots) play a key role in the automation of internal logistics, especially in the transport of heavy loads such as Euro pallets. Our goal was to create an autonomous robot designed for the efficient transport of materials (especially Euro pallets) in an industrial environment, while also being able to work in the narrow spaces, typical for production halls and warehouses. Figure 1 shows a 3D model of the vehicle built by Pro-Assem.

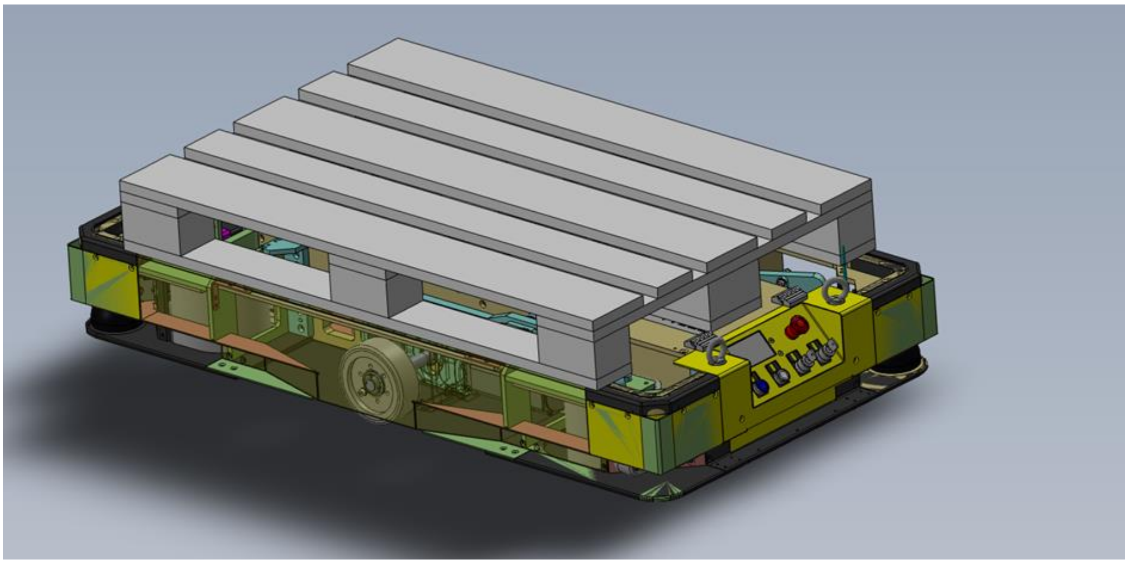

Fig. 1. 3D model of an AMR adapted for transporting Euro pallets

2.1. Requirements and design assumptions

The design process began with defining key requirements based on the needs of potential customers and analysing operating conditions. Particular attention was paid to the ability to operate in confined spaces, which significantly influenced the choice of vehicle geometry. Minimising the dimensions while

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maintaining adequate stability, manoeuvrability and load capacity was the main design challenge. From the point of view of starting the project, it is crucial to define the basic functional parameters of the vehicle. The parameters we adopted are described in Table 1.

Table 1. Design parameters of the autonomous forklift AMR

Parameter	Value	Comment
Lifting capacity	min. 1100 kg	The trolley was designed to transport loads weighing 1 tonne. A reserve of 100 kg was allocated for trolley accessories, including lifts constituting a separate module.
Width	max. 800 mm	A key parameter enabling movement in narrow areas, including those that were previously reserved for pedestrians only.
Length	max. 1650 mm	
Maximum speed	1,2 m/s	Although faster robots are available on the market, the number of obstacles in a typical factory environment usually prevents their full utilisation. The adopted value was considered optimal from the point of view of safety and efficiency.
Maximum terrain slope	3°	
Maximum unevenness	10 mm	Ensuring stability on typical industrial floors

3. Chassis

The design of the autonomous forklift chassis is crucial for its dynamic characteristics, safety and operational efficiency. During the design phase, particular attention was paid to ensuring even wheel pressure on the ground. This solution ensures that the braking distance remains constant regardless of the robot's load, which is fundamental for safety in industrial environments.

A chassis design based on three swing arms with six wheels was used. Figure 2 shows a visualisation. This solution ensures an even distribution of load on each wheel, reducing the issue to three points of weight support on the control arms. This is crucial when designing an emergency braking system. The predictable friction force allows for the precise design of safety zones.

Fig. 2. Photo of the drive wheel suspension arm in the designed robot

An alternative solution is suspensions using spring-based swing arms. Although such designs work well in lighter robots, cars and off-road vehicles, they are not optimal for heavy industrial robots. A vehicle in a factory is designed to operate on a level floor where shock absorption is not required.

3.1. Selection of drive motors

Selecting the right drive motors was one of the key design challenges. It was necessary to find a motor that would fit into a tight space, deliver relatively high power and meet safety requirements.

In mobile robots, especially those designed for industrial and outdoor use, the ability to overload the motors is crucial. In this case, the choice is mainly between servo motors (PMSM or BLDC) and asynchronous motors.

Servos are smaller and can withstand up to 3 times overload, but only for a very short time, usually 2-3 seconds according to the manufacturers' specifications. In this context, asynchronous motors may prove to be a better choice than servo motors, even though they have a lower power-to-weight ratio, they can be overloaded with much less current, but for a longer period of time. With good cooling, even continuously. With proper control, asynchronous motors provide maximum torque even at very low speeds and are also up to twice as cheap as servo motors.

Mobile robots do not require as extreme control precision as manipulators or CNC machine tools, and motor weight is not a critical parameter – the ability to generate high torques in demanding situations (overcoming thresholds, starting with heavy loads, driving on ramps) is more important. Asynchronous motors, thanks to their ability to withstand longer overloads with adequate cooling, provide better performance in such conditions. Since space was a priority for us, we decided to use servo motors.

3.2. Consequences of choosing geometry and engines – impact on dynamics

The choice of chassis geometry and drive system parameters has a direct impact on the robot's dynamic characteristics. Dynamic characteristics are crucial in safety design.

The initial design assumption was that a narrow trolley design (800 mm) would provide better manoeuvrability in confined industrial spaces. In practice, the combination of a narrow and elongated chassis (length to width ratio ~2:1) with a differential drive proved problematic for dynamic changes of direction. Figure 3 shows the wheel layout in a differential drive and support wheels.

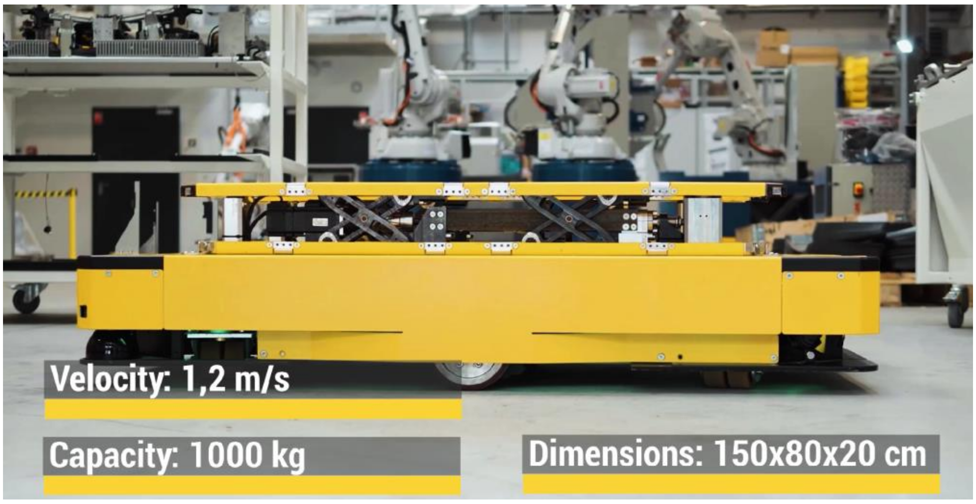

Fig. 3. Presentation of an AMR with a differential drive system

In a differential drive, torque is generated by the difference in driving forces between the left and right wheels, acting on an arm equal to half the wheelbase. In our design, due to the narrow chassis, the drive wheels acted on a very short arm relative to the centre of mass of the trolley. The consequences of this were:

- Low angular acceleration – low torque resulting from the short arm of force.
- Low useful force during rotation – a significant portion of the available drive torque was used to generate rotational motion at the expense of linear acceleration.
- High angular velocity – necessary for rotation, which was not a problem.

4. Safety

4.1. Hazard identification

The list of hazards associated with the operation of autonomous forklifts is extensive. It is the designer's responsibility to identify and eliminate or minimise the risks to an acceptable level. The main hazards associated with AMRs include:

- Crushing – directly running on a person standing between the goods being collected and the vehicle.
- Collision – hitting a person standing near the traffic lane.
- Collision with an obstacle above the range of the scanners – e.g. a parked forklift with raised forks.
- Loss of navigation – leading to uncontrolled movement.
- Slipping on substances that reduce friction – oil, powder, water.

4.2. Fundamentals of safety zone design

The basis for calculating safety zones is a model of the vehicle with its load, which must not collide with any obstacles in its path. The detailed scope of tests is based on the PN-EN ISO 3691-4 standard (Piltz, 2023) and the guidelines of the manufacturer of safety equipment, e.g. laser scanners (Tomasik, 2024). The approach may vary slightly depending on the equipment used, but the goal remains the same – to ensure a safe stop in front of an obstacle under all operating conditions.

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The classic approach involves the use of three zones inside the security scanner:

- Emergency zone – Entering this zone requires immediate emergency braking. It is a safety zone in the strictest sense of the word, requiring the most stringent testing.
- Warning zone – Any violation of this zone is transmitted to the control computer and causes the vehicle's speed to be reduced in such a way that the Emergency zone is not violated. If the speed is reduced by an order of magnitude, the Emergency zone will also be reduced by an order of magnitude.
- Warning 2 (pre-warning zone) – This zone is an order of magnitude larger than the Warning zone. Its size often corresponds to the Warning zone for the next higher speed. Information about violations is transmitted to the control computer, which then knows whether it can increase the speed.

4.3. The process of designating the Emergency zone

The preparation of the emergency zone consists of two stages:

1. Calculation of the theoretical braking path
2. Physical tests and corrections

To calculate the braking path, prepare a script (e.g. in Python or MATLAB) that takes into account the dimensions of the vehicle and its cargo, as well as the braking dynamics. The key parameters are: maximum braking deceleration, system response time, maximum speed, and the geometry of the vehicle with its cargo.

The dimensions of the transported load are also an important aspect. If the load exceeds the outline of the trolley, appropriate corrections must be made in the defined safety zones. Figure 4 shows a robot transporting a hardening bath that is larger than the vehicle.

Fig. 4. AMR transporting goods larger than the outline of the trolley

4.4. Zone discretisation

Due to the limited number of safety zones available in popular controllers (e.g. SICK, Hokuyo), zones are constructed for specific speed ranges. In our solution, we decided to use discretisation for speeds: 0.1; 0.2; 0.3; 0.5; 0.7; 0.9 and 1.2 m/s.

Furthermore, to increase the dynamics of the zones and minimise their excessive size, we have introduced zones dependent on the direction of movement (angular ranges). This allows for asymmetrical shaping of the zones – narrower when driving straight, wider to the side when turning.

4.5. The problem of changing direction during braking

According to our observations, most AMR manufacturers focus primarily on straight-line braking, without taking into account the fact that the robot's direction of travel may change during the braking sequence. This is difficult to verify, as actual safety tests are conducted with the Warning and Warning2 zones disabled, while demonstration presentations take all assistance systems into account.

The main reasons for ignoring best practices for creating side zones in mobile robots are:

- Difficulty in testing methodology.
- Increasing side zones significantly reduces trolley dynamics.
- Larger zones reduce operational efficiency (the robot slows down or stops more often for reasons that are not apparent to untrained persons).

The calculations should take into account that between the moment the obstacle is detected and the moment braking physically begins, the speed and direction of the robot's movement may change. The main factors introducing this delay are:

- Data processing and transmission time between the scanner and the controller.
- Inertia of the braking system (electromechanical delay).
- Control algorithm response time.

4.6. Zone shape considering the change of direction

When calculating the size of the zone in front and to the sides, we considered the maximum range of movement of the trolley from the moment an obstacle was detected, both in the longitudinal and transverse directions.

Considering the case where the trolley was turning when it received the stop command, the actual starting position will be position 3, not 1. As can be seen in Figure 5, position 3 extends not only further sideways (left), but also further forward. This means that the safety zone must be designed as the envelope of all possible braking trajectories, not just for straight driving.

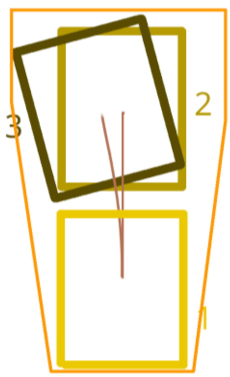

Fig. 5. Comparison of safety zones: position 1 – initial position of the trolley; position 2 – position after stopping when driving straight; position 3 – actual position after stopping when turning; orange outline – safety zone taking into account the worst-case scenario

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5. The relationship between chassis geometry and safety zone size

Previously, we discussed the impact of geometry on trolley dynamics (Chapter 4) and issues related to the design of safety zones (Chapter 3). It is time to combine these two aspects and show their direct relationship in the context of AMR vehicles.

The type of chassis selected has a key impact on the vehicle's ability to change direction when braking, which directly translates into the required size of safety zones. AMRs with steer wheel drive generally have negligible deviations in direction change from the moment an obstacle is detected. In differential drive vehicles, the change in direction can be significantly greater, depending on the width of the drive wheel track.

The change in angular velocity in a diff drive vehicle can occur for various reasons:

1. Angular acceleration in system response delay – the most common case of relatively minor significance. It occurs in the short time interval between the detection of a zone violation and the physical start of braking. During this time, the robot continues to follow its previously planned trajectory, which may include a turn.
2. Disruption of the direction of movement by floor obstacles – less common, but more dangerous. The appearance of a small obstacle (e.g. a screw) in the path of an AMR can disrupt the direction of the vehicle's movement, especially in a narrow chassis with a long base, where this effect is amplified.

As shown in Chapter 2, the narrow design of our trolley (800 mm) combined with the differential drive leads to increased sensitivity to changes in direction. This directly translates into the need to design wider side zones, which, as mentioned in Chapter 3, reduces the robot's dynamics and operational efficiency.

6. Optimisation of safety zones

The geometry of the constructed robot, combined with a rigorous approach to safety, significantly reduced the vehicle's dynamics. The problem was strongly felt in practical operation – the robot often slowed down in situations where it was not necessary from a safety point of view. Therefore, we decided to optimise the zone system.

The first idea was to increase the number of safety zones, including zones dependent on the steering angle. However we encountered two fundamental problems here:

- Hardware limitations – safety controller manufacturers limit the number of definable zones to 32 or 128, depending on the manufacturer.
- Verification costs – each defined zone must undergo detailed testing for compliance with the standard, which significantly lengthens and increases the cost of the certification process.

The need called for greater creativity. The key aspect of optimisation resulted from an analysis of the problem: a significant slowdown of the vehicle is not caused only by the Emergency zone, but also by the Warning 1 and Warning 2 zones. The Warning 1 zone must be large enough so that, from the moment an obstacle is detected in it, the vehicle has time to slow down enough not to violate the emergency zone. This means that in the classic approach, this zone extends far beyond actual needs, stretching in all possible directions, not just the one in which the trolley is actually moving.

It is important to note that Warning 1 and Warning 2 zones are not safety features, but merely auxiliary elements. Only the Emergency zone serves as a safety feature, and it must be certified and tested in accordance with the most stringent requirements.

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Since warning zones are not subject to functional safety requirements, they can be transferred from the safety controller to a regular computer, enabling the use of more complex algorithms. What is more, a smooth, dynamic change of these zones can be implemented depending on the predicted movement path.

Figure 6 shows a visualisation of the change in approach to the design of warning zones. In both cases, black indicates AMR, red indicates the Emergency zone (certified), yellow indicates Warning 1, and blue indicates the predicted trajectory of movement. For simplicity, Warning Zone 2 has been omitted, as its shape changes in the same way as Warning Zone 1.

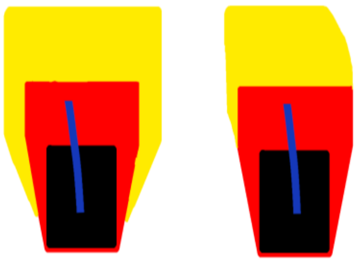

Fig. 6. Visualisation of the change in approach to the design of warning zones

Classic approach (left panel): Warning Zone 1 has a fixed, symmetrical shape calculated for the worst-case scenario.

Optimised approach (right panel): Warning Zone 1 has a shape that is dynamically adjusted to the predicted trajectory of movement.

The change in approach has brought two key benefits:

1. Increased average travel speed – the robot slows down less often in situations where it is not necessary from a safety point of view (driving straight near side objects)
2. Improved ride quality – avoiding unnecessary speed changes results in smoother movement, lower energy consumption, and a better experience for operators working near the robot

It should be emphasised that the optimisation did not affect the level of safety – the Emergency zone remained unchanged and still guarantees stopping before an obstacle in accordance with the requirements of PN-EN ISO 3691-4. Only the auxiliary zones have changed, which is acceptable from a certification point of view.

7. Summary

This article discusses the essence of selecting the geometry of a mobile robot and its impact on other aspects such as the choice of motors and safety design. There are many more similar relationships. This makes the creation of a high-quality mobile robot a challenge, and the development of a project aimed at creating a truly high-quality machine requires constant revision of the design, often forcing changes to the basic assumptions.

As part of the Regional Operational Programme for the Małopolska Region for 2014-2020, Pro-Assem carried out a project involving R&D work, which resulted in the creation of a prototype of an autonomous AMR transport trolley equipped with a lift or pick-up device.

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