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The Concept of an Autonomous Mobile Robot for Automating Transport Tasks in High-Bay Warehouses

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ABSTRACT

The progression of the industry, alongside the continuous enhancement of operational efficiency and the reduction of production costs, are paving the way for novel solutions in the realm of storage and transportation systems. The incorporation of new technologies and solutions, such as mobile robots, has culminated in the establishment of Smart Warehouses. It facilitates the reduction of non-value adding activities for companies. One of the methods of improving the efficiency of such systems is the more effective use of autonomous mobile robots. The article presented an inventive concept of an autonomous mobile robot capable of undertaking transport tasks both on the shop floor and within high-bay warehouses. The new concept of the drive mechanism enables it to navigate on surfaces and move along rail guides. By using an elevator, the robot can be lifted to higher levels within the warehouse. The well-conceived structural solution of the robot allows the elevator placement anywhere within the warehouse, eliminating the need for constructing a pit. The use of a mobile robot with the proposed structure will enable the execution of transport tasks without necessitating reloading. Such an approach has the potential to increase efficiency and reduce the costs of storage processes.

Keywords: autonomous mobile robot, elevator, automation, smart warehouse, intralogistics.

INTRODUCTION

The development of industrial technologies spans four distinct periods of time and is known as "revolutions". Each period is associated with a significant technological invention. The First Industrial Revolution was initiated by the invention of the steam engine. The Second Industrial Revolution was related, among other factors, to the invention of electricity and the introduction of mass production. New technologies such as programmable logic control and computer numerical control are characteristic of the Third Industrial Revolution. Today, we are experiencing the Fourth Industrial Revolution, characterized by a new manufacturing model called Industry 4.0 or the Smart Factory.

This model integrates various areas of automation and information technology. The main goal is to enhance decision-making capabilities and optimize production processes. The Industry 4.0 framework includes six design principles, Pereira et al. [1]:

- decentralization – distributed decision-making capabilities at different levels of the production systems. It allows for greater autonomy and responsiveness,
- real-time capabilities – they enable decision-making in real-time by ensuring an appropriate time for data receiving, collection, analysis, and sharing,
- modularity – it allows flexible adoption to meet changing production requirements by using a modular system design,
- interoperability – made possible by the ability of people and things (machines, devices, etc.) to collaborate through communication with each other and information exchange,

- virtualization – through the creation of virtual models of the physical manufacturing environments, including objects and processes, it enables simulation, monitoring, and optimization of processes,
- service orientation – it provides easy access to useful services, products, and information. It includes concepts like product-as-a-service.

Due to these principles, the Industry 4.0 model is smarter and significantly more advanced compared to the traditional manufacturing approach. This model is based on nine new technologies, which play a crucial role in this model and are known as the pillars of Industry 4.0, Rüßmann et al. [2], Forcina [3], Hernández-Muñoz [4]:
- industrial internet of things,
- big data and analytics,
- integration of systems,
- simulations,
- cloud computing,
- augmented reality
- additive manufacturing,
- cybersecurity,
- autonomous robots.

Autonomous mobile robots are one of the main pillars of Industry 4.0. Their dynamic development is a reaction to increasing intralogistics requirements. Unlike AGVs, AMRs do not need an external system to localize themselves and are equipped with sensors as well as cameras to navigate their environments. AMRs will allow manufacturers to create more efficient transportation systems while developing their plants, according to Javaid et al. [5]. The increased responsiveness in production is possible by implementing a material handling system based on AMR that can adapt quickly to changes. Therefore, AMRs in production systems can improve manufacturing efficiency in terms of productivity, flexibility and costs, as reported by Fragapane et al. [6]. In summary, the efficiency of production systems depends on the effective flow of goods, e.g., within warehouses. Automation in warehouses, known as Smart Warehouses, allows for the efficient management of stock volume, leading to lower costs. New technologies, such as Artificial Intelligence (AI), are very often implemented in mobile robots, increasing their autonomy. Therefore, robots can replace humans in performing physically demanding activities and also have the ability to cooperate with and learn from them. These functionalities allow for the improvement of productivity in manufacturing systems and the efficiency of Smart Warehouses. At the current stage of development of automated transport systems in the area of intralogistics at the shop floor level, technologically advanced AGV and AMR vehicles are at disposal. Many specialized solutions are available to perform transport tasks inside high-bay warehouses; however, there are no transport vehicles that can service both of these areas (shop floor and high-bay warehouses).

The goal of the paper was to present the design of autonomous mobile robot dedicated to transporting loads on pallets, on shop floor and in high-bay warehouses.

BACKGROUND

Mobile robots

The beginnings of the construction of mobile robots date back to the 1950s when research and work on Automated Guided Vehicles (AGVs) began. The history of the development of such mobile robots is presented in detail by Ullrich [7]. Originally, AGVs were used to transport goods in the warehousing and logistics industries, both indoors and outdoors and can be divided into the following types: towing vehicles, unit load vehicles, pallet truck and forklift, in line with Lynch et al. [8]. AGVs require guidance systems to navigate through their environment. They can accomplish tasks by following a predetermined path autonomously. This type of robot usually localizes or drives along physical guidelines on or within the floor. In this case, inductive, magnetic, or optical track guidance can be used. Another solution is to use transponders, QR codes, laser navigation with reflectors, or the Global Positioning System (GPS). Robot localization precision and performance depend on applied algorithm. A new method to localize a mobile robot based on graph theory in a tree and network topology was proposed by Ashoori et al. [9]. To enhance better localization results, information from more than one source (sensor) is needed. This type of information merging is called sensor fusion, as described by Reis et al. [10], Di et al. [11].

For many decades, AGVs have been widely used in the automation of transport systems. However, due to their method of navigation, they have limited flexibility in implementing transport tasks.

The development of new navigation methods, e.g., based on lidar Simultaneous Localization and Mapping (SLAM) or Visual SLAM, and control systems based on the Robot Operating System (ROS), enables the construction of Autonomous Mobile Robots (AMRs) that have the ability to, for example, choose routes and avoid obstacles. A comparison of the development and functional capabilities of AGVs and AMRs was described by Zhang et al. [12]. Due to their functionality, AGVs are used to carry out three basic types of tasks: material handling, replacement of manual work, and acting as a mobile workbench. The main advantages of AGV applications include the reduction of labor, accidents, pollution, and power consumption, as well as the tracking of goods. On the other hand, compared to AGVs, AMRs are generally regarded as mobile robots with a high level of autonomy.

Among other factors, the functional possibilities of wheeled mobile robots depend on the design of their drive mechanism. The basic parameter of mobile robots is the number of wheels. There are designs with two or more wheels. The most popular solution is a robot chassis consisting of six wheels. Two drive wheels are placed on the sides, halfway along the length of the robot. The load-bearing trailing wheels are positioned at the corners of the chassis. An example of such a solution is shown in Figure 1.

Controlling the movement of a mobile robot requires developing an appropriate mathematical model for the kinematics and dynamics of its drive system. A new, universal methodology for dynamics modeling was proposed by Trojnacki [13]. Advanced knowledge in the field of modeling, identification, and control of nonlinear systems, using the example of wheeled mobile robots was presented by Giergiel et al. [14]. Mobile robots, including autonomous ones, are already commonly used to perform inter-station transport tasks. They usually carry loads on a single shop floor level, such as from production lines to warehouses or vice versa.

Smart warehouses

The activities related to transport and storage do not generate added value to the product; however, they are indispensable components of manufacturing processes. Since these activities increase costs, efforts are made to reduce them by introducing modern technologies in the area of lifting and storage equipment that work both indoors and outdoors, as reported by Miądlicki et al. [15, 16]. Recently, the development of the logistics market driven by the increase in e-commerce, mass customization, omni-channel distribution, and the just-in-time philosophy has been observed. Automation applied in warehouses is the answer to this dynamic change. Custodio et al. [17] present a comprehensive literature review as the research method for this case. In this study, 113 scientific papers from WOS, Scopus, and IEEE Xplore were analyzed between January 2008 and December 2018. The average number of

Figure 1. Autonomous Mobile Robot – MIR100 with roller feeder

publications on this topic increases year by year. They conclude that the critical point to achieve flexibility in an automated warehouse is the combination of automated equipment, data collection technologies, and management solutions. A systematic literature review conducted by van Geest et al. [18] reveals a growing interest in smart warehouses among researchers over the years. The majority of articles are from recent years. There are various types of devices and mobile robots dedicated to handling different types of warehouses, including various kinds of high-bay warehouses. To effectively utilize warehouse space, high-bay warehouses are frequently used. Stacker cranes are commonly implemented to automate their handling. An example of this solution is presented in Figure 2. For the warehouses equipped with rail guides, automated load handling is accomplished using controlled shuttle vehicles, as depicted in Figure 3. This storage solution enables more efficient utilization of warehouse space, but necessitates the transfer of loads from a forklift or mobile robot to a shuttle vehicle, which then facilitates transportation within the depths of the warehouse.

To enhance automation levels and improve the efficiency of storage processes, specialized shuttle movers, working in conjunction with elevators, are utilized. Palletized loads are delivered

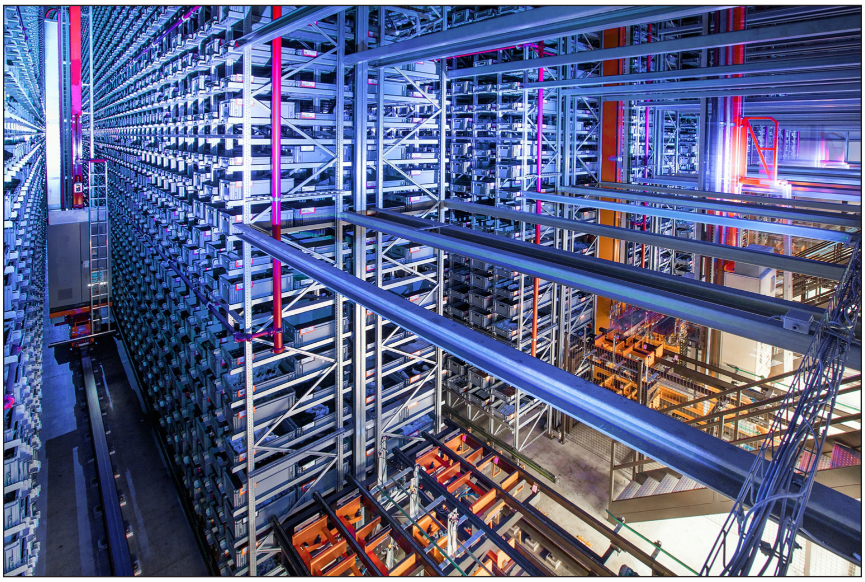

Figure 2. Miniload stacker crane - source PROMAG S.A. [19]

Figure 3. AutoMAG Shuttle semi-automatic dense storage system – a proprietary system by PROMAG S.A. [20]

to the lift by a forklift, mobile robot, or roller conveyor, where the shuttle and mover are positioned. Once the lift reaches the designated level, the mover transports the pallet, positioned on the shuttle, to the appropriate location within the warehouse. Subsequently, the shuttle transports the loaded pallet deep into the warehouse. This solution is presented in Figure 4.

An extension of the solution discussed above is the RAFT AS/RS (Automated Storage/Retrieval System) [22]. It represents a 3-dimensional 'lift and run' system. Pallets are elevated to the designated warehouse level and then transferred both across lanes and down lanes to the next available pallet position. This solution uses a mover with a specialized design capable of orthogonal movement in two directions. Another significant and extensive category comprises warehouses catering to the e-commerce industry, like the RoboShuttle System [23]. These warehouses typically feature dual-rack modules designed for containerized item storage. The process of storage and product retrieval is facilitated by specialized mobile robots. The system combines the RoboShuttle, responsible for vertically transferring totes between storage and buffer shelves, with a standard mobile robot assigned to transport the chosen tote to the picking workstation. Another interesting solution for the e-commerce industry is the AutoStore system [24], which uses a large cubic grid housing 28,000 bins and 22 robots that glide over the grid. This solution eliminates wastage of warehouse space by occupying approximately 30-40% of the space required by rack storage. An interesting warehouse solution for e-commerce logistics was proposed by Hu [25]. This solution integrates an auto-access multilevel conveying device with three-dimensional movement into an AS/RS system.

Smart warehouse systems are widely used in various industrial areas to achieve cost-effective utilization of equipment, space, and time. Their effectiveness depends, among other factors, on storage location policies, batching, and routing procedures. Manzini et al. [26] proposed an approach to the design and control of an AS/RS based on modeling and simulation. Jardzioch et al. [27] presented an approach to a closer analysis of the simulation model of high storage sheet depot. An approach based on a dynamic warehouse allocation model was proposed by Chi et al. [28]. This approach aims to establish a robotic mobile fulfillment system within an AS/RS, with the goal of minimizing the handling distance. An algorithm based on a method to find the storage location and the optimal route for AGVs in a rectangular 2-block warehouse was proposed by Bao et al. [29]. The effectiveness of this method was verified through a simulation experiment.

During the operation of e-commerce warehouses, numerous orders often arise simultaneously. The solution to this problem is proposed by Li et al. [30]. They introduced a novel scheduling mechanism for multi-robot and task allocation problems based on swarm optimization heuristics. Liu et al. [31] proposed a Cyber-Physical Systems (CPS)-based smart warehouse in the era of Industry 4.0. One of the technologies for building smart warehouses is multi-robot coordination. A comprehensive review of the problems and

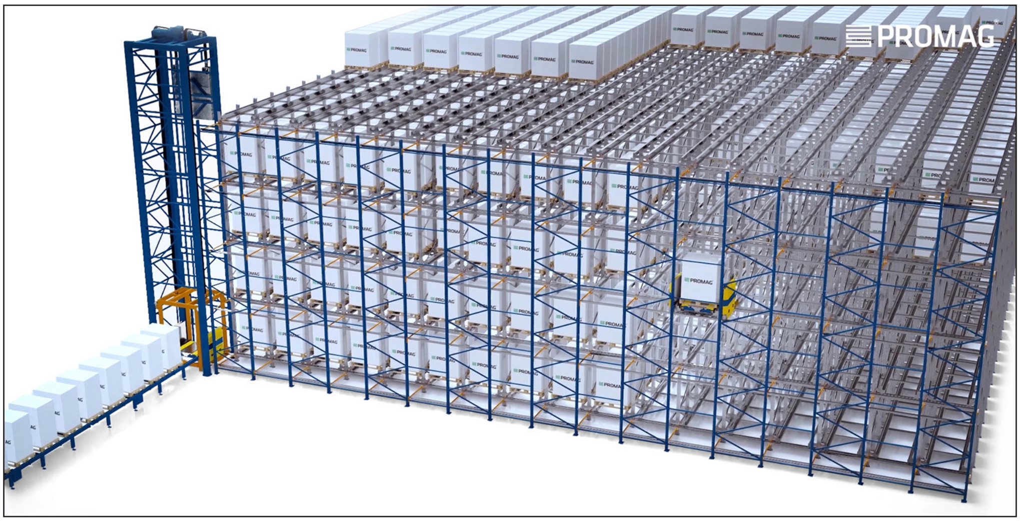

Figure 4. AutoMAG Mover automatic dense storage system – a proprietary system by PROMAG S.A. [21]

solutions in the field of smart warehouse management was presented by Zhen et al. [32]. In this work, they focus on information interconnection, equipment automation, process integration, and environmental sustainability.

The solutions described above, both in the field of transporting loads on pallets and in containers for the e-commerce industry, require reloading on a different device throughout the entire transportation process. The utilization of a mobile robot, designed to eliminate the necessity for reloading, can enhance efficiency and lower transport costs, particularly in the scenario of palletized loads. Therefore, the works to solve this problem were successfully undertaken at Laboratory of Industry 4.0 Technologies at Cracow University of Technology. A patent (Pat.240289) has already been obtained in this regard, and another new solution is presented in this article.

MAIN FUNCTIONAL ASSUMPTIONS

Before developing the new concepts and construction solutions for a mobile robot intended for transportation tasks, its functionality should be precisely defined. Special attention should be given to the types of transport tasks it is meant to perform and the environment in which it will operate. The objective is to formulate the concept of a mobile robot capable of transporting loads at shop floor level and delivering them to high-bay warehouses. In this scenario, during the transportation task, the autonomous mobile robot operates in various environments. It needs to navigate the shop floor, move between different levels of the rack warehouse (e.g., using an elevator), and transport loads along rail guides deep within the warehouse.

To guarantee clear navigation in these diverse environments, the presented concept must incorporate a hybrid solution. The robot's control system should enable autonomous task execution and wireless communication with the fleet management system and the warehouse management system. The robot's driving mechanism should enable it to navigate the shop floor level, enter the elevator, ascend to the designated level of the high-bay warehouse, move along the floor between the racks, and subsequently transport the load along the rail guides to the rack interior. In summary, the main required functionalities of an autonomous mobile robot should include:

- ability to navigate the shop floor,
- capability to transport pallets,
- ability to enter and exit elevators, accessing different warehouse levels,
- capacity to drive along guides deep into the warehouse,
- navigation system based on sensor fusion for versatile environment navigation,
- autonomous control system,
- wireless communication.

AUTONOMOUS MOBILE ROBOT CONCEPT

Considering the aforementioned assumptions, a concept for a mobile robot designed to transport loads on pallets has been proposed. The general design solution is depicted in a simplified manner in Figure 5. Figure 5a shows the external view of the robot. The robot's body (1) is equipped with a pallet lifter (2) featuring base pins (3). In the presented concept of a mobile robot, a hybrid solution for the localization system has been proposed:

- optical sensors (4) – for positioning the robot within the rail guides,
- ultrasonic sensors (5) – included as part of the safety system to detect obstacles, particularly glass walls,
- three laser rangefinders (6) – for accurately positioning the robot during load pickup and drop-of,
- emergency stop (7),
- a depth camera (8) – integrated into the safety system to identify obstacles in the space ahead of the robot,
- laser scanner (9) – for lidar simultaneous localization and mapping (SLAM) as well as for security purposes,
- camera – for reading QR codes positioned on the floor and for adjusting the robot's location.

Figure 5b provides a simplified depiction of the robot's internal view, highlighting its main components:

- battery (10),
- pallet lifting actuators (11),
- camera (12) – for reading QR codes,
- housing containing the robot's drive system (13).

The robot's drive mechanism, which is the focus of the patent application, is illustrated in Figure 6. The key components of the drive mechanism are detailed in Figure 6a and b.

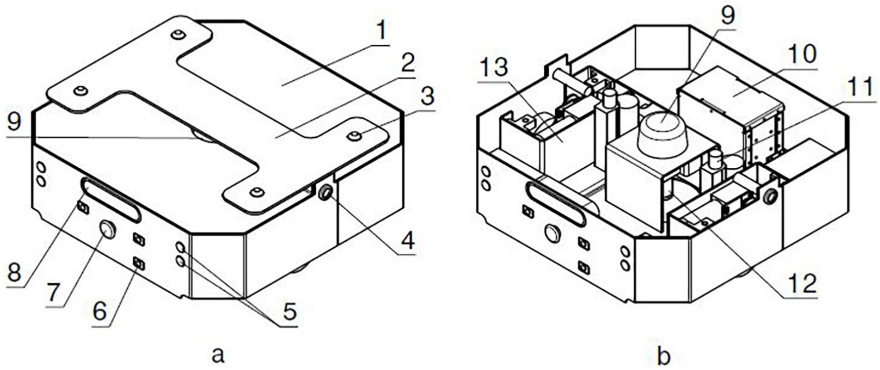

Figure 5. Simplified external a) and internal b) robot views: 1 – robot body, 2 – pallet lifter, 3 – base pin, 4 – optical sensor, 5 – ultrasonic sensor, 6 – laser rangefinder, 7 – emergency stop, 8 – depth camera, 9 – laser scanner, , 10 – battery, 11 – actuator, 12 – camera, 13 – drive system housing

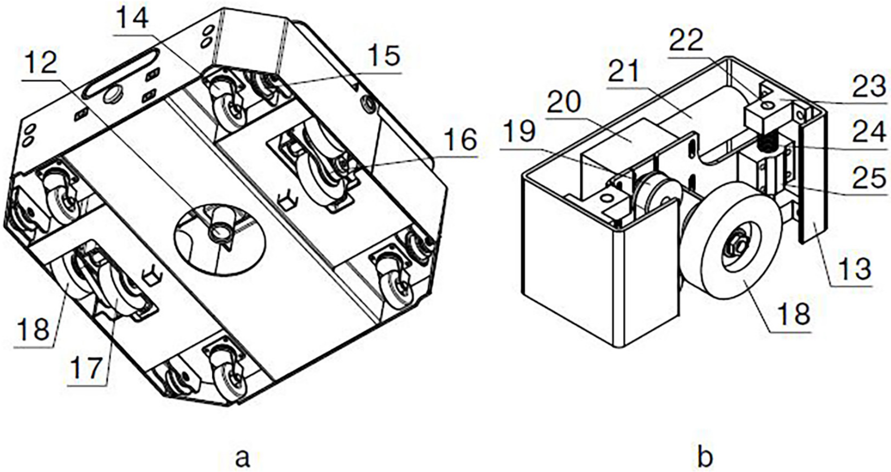

Figure 6. The mobile robot drive mechanism views; a) bottom robot view, b) drive mechanism view;12 – camera, 14 – trolley wheel, 15 – flange roller, 16 – belt drive, 17 – driving wheel on floor, 18 – driving wheel on rail, b) 13 – drive system housing, 18 – driving wheel on rail, 19 – toothed belt, 20 – gearbox, 21 – DC motor, 22 – linear guide shaft, 23 – holder, 24 – spring, 25 – linear bearing

When the robot is moving on the floor, it utilizes four trolley wheels (14) that serve a load-bearing function. The driving functionality is executed by two wheels (17) positioned on the sides of the robot along its axis of symmetry. This configuration enables the robot to turn in place around its own axis. It is a classic solution for the drive mechanism, analogous to the one presented in Figure 1. To enable the robot to enter the rail guides, it has been equipped with four additional wheels (15) flange rollers. These wheels are positioned at the correct height to facilitate easy entry from the floor. Two additional wheels (18) are used to propel the robot along the guides. The construction of two symmetrical drive mechanisms is illustrated in Figure 6b. A belt transmission with a toothed belt (19) transfers power to the wheels (17) and (18) from the gearbox (20), which is driven by a DC motor (21). The entire drive mechanism can move vertically by linear bearings (25) along the guides (22) fixed to the housing (13) by fastening blocks (23). The pressure of the wheels against the ground or rail guides is realized by springs (24). Detailed views of the drive mechanism are presented in Figure 7. The presented drive mechanism solution makes it possible to build an elevator that moves the robot without requiring a pit. Owing to this, the implementation of the entire storage system is possible without affecting the floor structure. It is illustrated in Figure 8a. When the robot moves on the floor (27) using wheels (14) and (17), at this time wheels (18) and (15) are positioned above the floor. This allows the robot to traverse over the elevator guides (26).

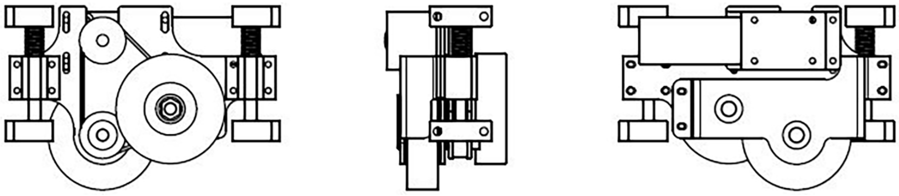

Figure 7. Views of drive mechanism

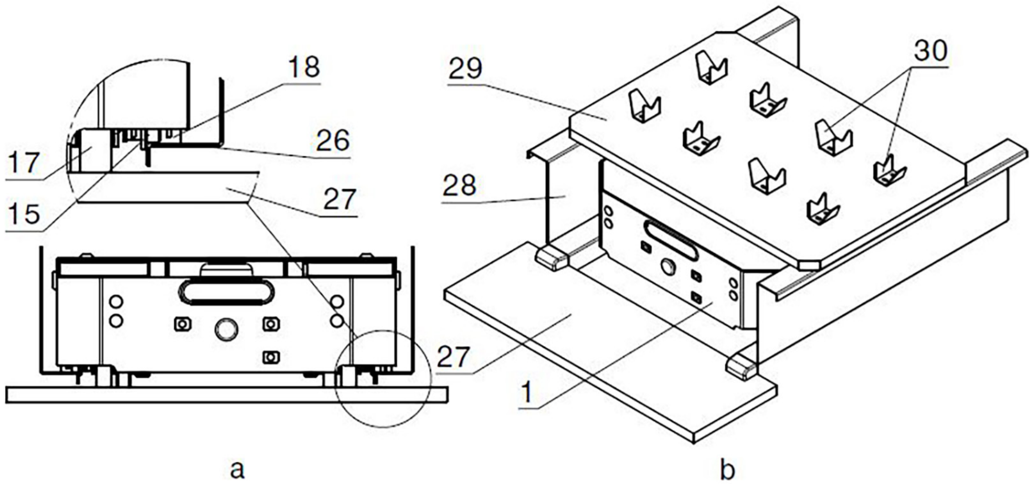

Figure 8. The views of the main components of robot drive mechanism which allow implementation of the entire storage system; 1 – robot body, 15 – flange roller, 17 – driving wheel on floor, 18 – driving wheel on rail, 26 – rail of elevator, 27 – floor, 28 – rail of racking structure, 29 – pallet, 30 – shaft holder

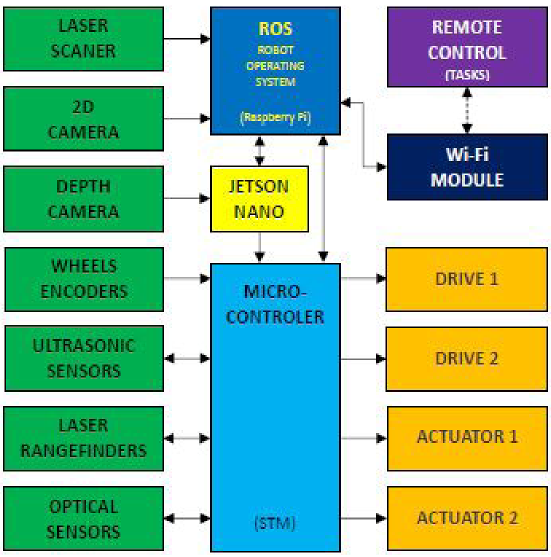

Figure 9. The block diagram of the control system

The elevator can then ascend, lifting the robot to the next floor level. Utilizing the floor on the next level, the robot can access the relevant rail guides. Next, after rotation, the robot can run into the target rail guides. This is depicted in Figure 8b. After the robot has reached its target position, it can, for example, pick up a pallet (29) with shaft holders (30). In the presented solution, the entire process of transporting a loaded pallet to a high bay warehouse can be executed without the need for reloading.

In the presented concept of a mobile robot, the control system is modular and built upon the ROS (Robot Operating System). Support for lidar SLAM navigation and QR code reading with a 2D camera is handled by the Raspberry Pi microcomputer. The safety system, based on a depth camera, is executed by the Jetson Nano microcomputer. Direct control of the robot's movement is managed by the STM microcontroller, which oversees drives and actuators, including sensor fusion. The input data from optical sensors, ultrasonic sensors, laser rangefinders, emergency stop mechanisms, and wheel encoders are integrated within the STM module. Furthermore, ROS enables Wi-Fi communication with mobile devices and external applications, such as mobile robot fleet management and warehouse system management. The block diagram of the control system is depicted in Figure 9.

CONCLUSIONS

The article introduced a novel concept for an autonomous mobile robot designed to execute transportation tasks on the shop floor level and across various levels of high-bay warehouses. The proposed drive mechanism enables the robot to navigate flat surfaces and traverse along rail guides within the warehouse. This construction facilitates load transportation by the robot without the need for reloading, potentially enhancing the overall efficiency of the storage system and reducing costs. Given the diverse environments the robot will navigate, an extensive positioning system is essential. The control system's block diagram, as proposed in the article, uses the sensor data fusion from various sources. Depending on the prevailing environment, the robot will utilize information from different sensor groups. Subsequent efforts will be directed towards constructing a prototype of the robot and deploying the control system in alignment with the developed concept. The following stage will involve implementing the robot to execute transport tasks within a testing environment and verifying the proposed solutions.

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