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Advancements in cooperative mobile robots control strategies for large-scale material transport: review

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Abstract
This paper explores groundbreaking advancements in control strategies for cooperative mobile robots used in large-scale material transport, a critical aspect of modern industrial, manufacturing, logistics, and construction sectors. It delves into the development of sophisticated systems that enable seamless coordination among multiple mobile robot systems. The research presents a novel hierarchical finite state automaton for dynamic mission adaptation and a null space-based control scheme for precise task execution and enhanced system resilience. The introduction of Mecanum wheels facilitates flexible movement and manipulation of materials, thereby increasing the operational efficiency and safety. Cutting-edge sensory technology, including LiDAR (Light Detection and Ranging), and the implementation of Robot Operating System are highlighted for their roles in enhancing autonomous navigation and intelligent operation. Additionally, the paper discusses the impact of centralized and decentralized control methods in ensuring safe cooperative object transport. The findings contribute to the vision of Industry 4.0 by promoting the integration of automation and robotic cooperation in complex environments and present a foundational blueprint for further research. Challenges for future work such as scalability, communication efficiency, collision avoidance, and energy efficiency are also considered, underscoring the need for ongoing development of robust and scalable robotic systems to address modern transport challenges.

1. Introduction
Mobile robots are gaining popularity in the industrial sector for transporting materials within production facilities [1]. For instance, they can move raw materials to the production line in manufacturing plants. In warehouses, these robots can streamline logistics by carrying goods from picking areas to shipping docks using a variety of technologies including conveyors, automated guided vehicles, autonomous mobile robots, and other types of robotic systems [2], [3]. They offer several benefits, such as increased efficiency, cost reduction, enhanced safety, and minimizing manual labor [4]. Furthermore, they can navigate through intricate environments while avoiding obstacles and adjusting to changes in their surroundings. Moreover, mobile robots can be easily programmed to execute repetitive tasks along specific routes, allowing human workers to concentrate on more complex and value-added activities [5].

In many situations, a single mobile robot may not be sufficient to manage extensive material transport on its own. In these cases, multiple mobile robots can cooperate to efficiently shift heavy loads or move materials across large industrial spaces [6]. By synchronizing their movements and responsibilities, these robots can work together effectively to meet the substantial requirements of large-scale material transportation. This collaborative method enhances overall productivity and throughput while also guaranteeing smooth and prompt delivery of materials within the industrial environments.

Multiple mobile robots offer several benefits compared to a single robot for material transport. One advantage is their capability to handle heavier loads and larger volumes of materials, increasing overall throughput and efficiency in an industrial environment. Additionally, using multiple robots provides redundancy and flexibility, allowing seamless operation during malfunctions or maintenance of individual units. Moreover, tasks can be evenly distributed among the robots to reduce congestion in a workflow [7]. However, managing and coordinating multiple mobile robots poses challenges such as requiring sophisticated control systems to ensure effective collaboration without collisions or conflicts. In some cases, the initial investment and maintenance costs may outweigh the benefits for smaller-scale operations [8].

In this paper, an examination of control systems for the transportation of large-scale materials using mobile robots in industrial environments is presented. The emphasis will be on the different technologies and approaches utilized to oversee and synchronize multiple mobile robots for effective and smooth material conveyance. Additionally, we will address the obstacles and factors linked with deploying and upkeeping control systems for extensive material transport, emphasizing the possible advantages and constraints of such systems in industrial environments.

A rare survey delves into cooperative large-scale material transport, with the most relevant papers referred to [9], [10], and [11]. Tuci et al. classified relevant papers on cooperative object transportation into three categories: pushing-only strategy, grasping-based strategy, and caging-based strategy [9]. Farivarnejad et al. focused on analyzing control strategies for cooperative object transport, categorizing algorithms based on centralized or decentralized control architecture: centralized, semi-centralized, or decentralized [10]. An et al. examined the basics of multi-robot systems, communication technologies, validation platforms, and simulators, as well as challenges in cooperative object transport [11].

This paper concentrates on two important areas of large-scale material transportation by multiple mobile robots: 1) the method for coordinating control and 2) the mechanical platform. Specifically, this paper's primary contributions are as follows: a) This review offers a thorough analysis of existing coordination methods for large-scale material transport using multiple mobile robots, which have a crucial role in coordination. b) A detailed comparison of commonly utilized mechanical platforms for multiple mobile robots is presented. c) An overview of recent researches on collaborative extensive material transport in industrial settings and their associated challenges is provided.

2. Multiple Mobile Robot Mechanical Platform

Mobile robot platforms that are designed to transport large and heavy materials in various industrial settings are equipped with advanced mechanical systems and control mechanisms that enable them to navigate through complex environments and carry out material handling tasks efficiently. The use of mobile robot platforms has revolutionized the way large materials are transported, offering a cost-effective and versatile solution for industries such as manufacturing, logistics, and construction. In this paper, we will explore the key features and benefits of mobile robot mechanical platforms, as well as their impact on improving productivity and safety in material transport operations.

The hardware design of the robotic platform featured in [12] integrates several key elements targeted at facilitating research and education in the field of cooperative robotics. The robot's hardware design presented in Figure 1 consists of (1) the use of three omnidirectional wheels as a significant feature, which provides the robot with the capability to move in any direction and essential for executing complex maneuvers during cooperative tasks and allows for agility in diverse operating environments, (2) two traction wheels complementing the omnidirectional wheels, which play a vital role in multi-robot object manipulation, contributing to the generation of the necessary forces for object handling and movement, (3) a mechanical manipulator employed for cooperative lifting of objects, which leverages a parallelogram design that passively lifts objects by applying pressure, allowing for friction-based gripping without the need for complex grasping mechanisms, and (4) the robot’s design to function both as a standalone unit and as part of a larger multi-robot system, which supports a range of cooperative tasks, including those that require multiple robots to lift and transport larger objects [12]. This hardware design encapsulates the requirements for a robotic platform to be utilized in educational contexts and research settings, where adaptability, ease of use, and effectiveness in cooperative scenarios are paramount. The platform's flexibility and focus on object manipulation and transportation encapsulate the growing need for robotic systems that can collaboratively handle complex tasks in dynamic environments [12].

The design of the robot platform in [13] incorporates a balanced approach across various domains, ensuring that each robot is functional. The main features and components of the robot platform design are: (1) An acrylic plate is used as the base of the robot, which is shaped using a laser-cutting process. (2) The robots are equipped with 6 V motors that have gear reduction to control the movement. (3) There are 4 Swedish-type omnidirectional wheels with a 0.6 cm diameter base, chosen for their adaptability to different surfaces and cost efficiency. (4) Four L298 motor drivers are incorporated, allowing for changes in motor rotation which is equipped with a DC-DC converter to standardize the voltage at 7.2 V and a 3000 mAh battery providing the required energy autonomy. (5) The robot includes various sensors for measuring speed and orientation. (6) The platform uses an Arduino DUE as the main control board responsible for data acquisition and the processing of sensor information. It was selected for its capacity to implement digital pins as interrupt pins, which are crucial for managing the sensors and actuators in real time. The design of the robot platform with four Swedish-type omnidirectional wheels shown in this multi-robot platform (Figure 2) are intentionally designed with open-source principles, so they can be easily replicated using readily available commercial components. The robots are also designed with omnidirectional mobility, which allows for more complex and varied movement patterns, suitable for collaborative robotics applications [13].

The design of a multi-wheeled mobile platform in [14] is centered around a holonic, homogenous, multi-agent system. This design incorporates multiple agents that apply Q-learning, an advanced form of reinforcement learning, to control individual wheels with precision. This structure allows for the decomposition of the platform's control system into smaller, manageable agents, each responsible for a specific module, like a system of multiple collaborative robots. The platform itself is built to handle substantial payloads, which is essential for industrial applications like the transportation of heavy components. Its modular architecture features four vehicle steering modules, each consisting of two wheels powered by separate motors. This enables each module to operate like a differential drive, granting the platform flexibility and agility in its movements [14]. The robot is illustrated in Figure 3. Figure 3 (a) presents the complete unit, while Figure 3 (b) focuses on a single driving module within that unit. The platform dimensions are 1.2 m in length and 0.8 m in width. The maximum manufacturer's payload is 500 kg, the battery capacity is 52 Ah, and all modules drive independently. To effectively coordinate the motion of these modules, the agents in the multi-agent system learn and adjust policies for both forward and angular velocities through training. The learning process comprises two parts: one focusing on module positioning to minimize orientation error, and the other on cooperative movement to synchronize velocities according to the desired position in the formation. This multi-agent design promotes efficiency in the mobile platform's motion control, allowing it to adaptively navigate while considering factors such as energy consumption optimization and optimal trajectory planning. It achieves an effective balance between computational load and system flexibility, making this design suitable for complex, real-world applications where collaborative and autonomous navigation is necessary [14].

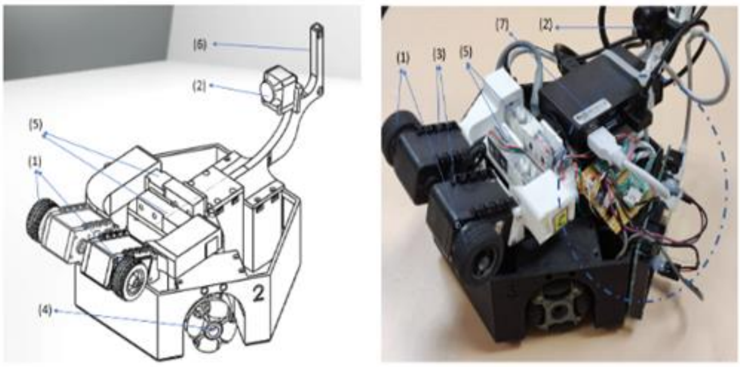

Figure 1. Omnidirectional Mobile Platform with Manipulator to Lift Object [12]

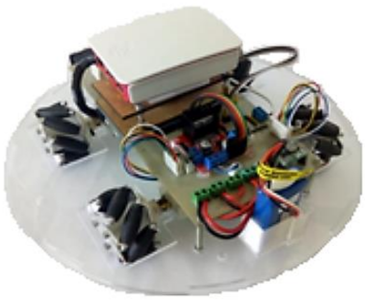
Figure 2. Robot Platform with Four Swedish-Type Omnidirectional Wheels [13]

Figure 3. Multi-wheeled Mobile Platform: *Mechanical Platform* (a); *Single Driving Module* (b) [14]

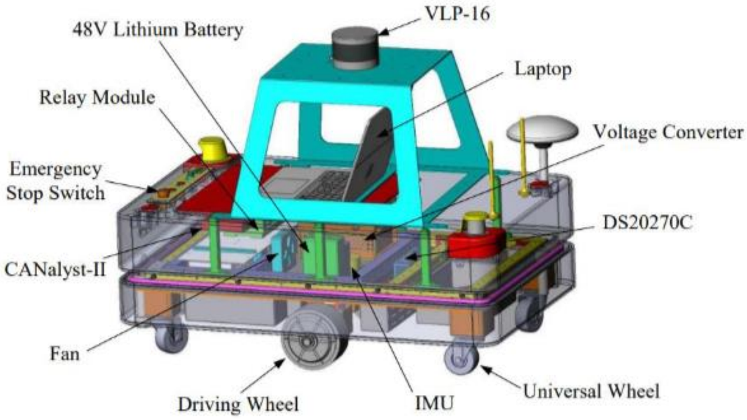

Figure 4. Structural Design of Mobile Robot Platform with Two Driving Wheels [15]

The robot's design in [15] aims for operational simplicity and strong scalability, making it suitable for various tasks from building patrols to warehouse logistics. The mobile robot's ability to autonomously navigate, plan paths, and construct maps is pivotal for its intelligence and autonomy. Furthermore, the paper underscores that although multiple experimental mobile robot platforms have been developed, they often lack scalability and are limited to fixed scenarios without the ability to expand functions easily. The design proposed in [15] addresses these limitations. By using a full suite of sensors, including LiDAR (Light Detection and Ranging) for three-dimensional environmental mapping and an Inertial Measurement Unit for navigation, the platform achieves accurate positioning, environmental perception, and dynamic obstacle avoidance. In addition, the platform's software system utilizes the Robot Operating System, which is a modular and flexible framework that enables the robot to perform complex tasks like real-time path planning and autonomous exploration. This approach allows the robot to navigate through multi-obstacle indoor scenes intelligently and autonomously. Key parameters of the mobile robot platform include a height of 0.75 m, width of 0.53 m, length of 0.86 m, and 4 m/s for travel speed [15]. The platform's design in [15] is presented in Figure 4.

The Savvy robot, created by [16], features a body structure and an omnidirectional mobile base to fulfill the needs of small indoor robots. Its three extendable layers create room for installing sensors and equipment, which increases its adaptability for various uses. With Mecanum wheels on its mobile base, the robot can move in any direction without altering its orientation. This design enables efficient navigation in confined indoor areas, making it well-suited for tasks that demand precise positioning and adaptable movement capabilities.

3. Control Methods for Large-scale Material Transport by Cooperative Mobile Robots

Large-scale material transport by cooperative mobile robots is a complex and challenging task that requires a sophisticated control system to ensure the efficiency and safety of the operation [17]. In this section, we will delve into the different control methods that can be utilized to facilitate the seamless movement of materials by cooperative robots. By understanding the intricacies of these control methods, we can identify the most suitable approach for maximizing the efficiency of material transport while minimizing potential risks and bottlenecks. After considering various methods for large-scale material transport by cooperative mobile robots, it is important to avoid methods that could potentially damage the object being transported. This includes methods such as grasping, pushing, or caging the object [9] [18]. Instead, it is better to consider methods where the object is carried on the top of the robot, ensuring safer and more efficient transportation.

Another important aspect of controlling large-scale material transport by cooperative mobile robots is the coordination of their movements [19]. This coordination can be achieved through centralized or decentralized control methods. One of the key control methods for large-scale material transport by cooperative mobile robots is the use of centralized control. This approach involves a single controller that coordinates the actions of all the robots involved in the transportation process [20]. The centralized control system can optimize the paths taken by the robots, allocate tasks efficiently, and prevent collisions or congestion in the workspace. Another control method is decentralized control, where each robot makes decisions autonomously based on its local perception of the environment and the tasks at hand. Decentralized control systems offer increased flexibility and robustness, as they can adapt to changes in the environment and handle unexpected situations [21]. Additionally, a hybrid control approach can also be employed, combining elements of both centralized and decentralized control [22]. This hybrid approach can leverage the advantages of both systems, providing the potential for efficient task allocation while maintaining adaptability to dynamic environments. Understanding the strengths and weaknesses of each control method is crucial for designing a control system that can effectively manage large-scale material transport by cooperative mobile robots. It is important to consider factors such as the size of the workspace, the complexity of the tasks, and the level of coordination required between the robots.

The cooperative carrying method for mobile robots described in the study [23] involves a centralized control system using an interval type-2 fuzzy neural controller. This approach enhances the coordination between robots during cooperative object transport, especially in unknown environments. The interval type-2 fuzzy logic enables the system to handle uncertainties effectively, such as sensor noise or environmental unpredictability, by providing a larger range of uncertainty in the membership values. This leads to improved robustness and adaptability of the controller, resulting in more reliable and precise cooperative carrying performance by the group of mobile robots. The control system uses a manager mode to switch between wall-following and toward-goal behaviors, determining the best strategy for navigation and object transport based on the robots' environment and positioning. In the study, two mobile robots carry an object, presented in Figure 5, cooperatively. These robots are positioned at a set distance from each other, with a rectangular object placed on top of them. The front robot acts as the leader, exploring the environment and guiding the movement, while the rear robot follows, assisting in lifting the object. Together, they cooperate to avoid obstacles and ensure the object is not dropped during transport. The two robots maintain a set distance of 15 cm between each other to carry out the task effectively [23].

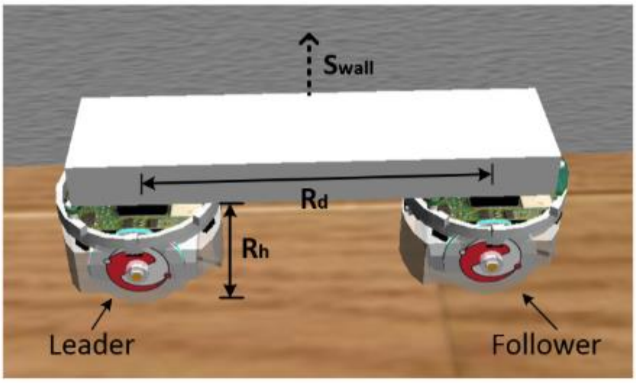

Figure 5. Centralized Cooperative Two Mobile Robots Carrying Object [23]

The cooperative controller for multiple nonholonomic mobile robots, as described in the paper [24] is designed through a distributed approach. This process involves several steps. Initially, a coordinate transformation and feedback mechanism are proposed to convert the original system dynamics of the nonholonomic robots into a new transformed system that is more manageable for control purposes. After transforming the system, a distributed controller is created using information from the intrinsic system dynamics and the neighboring robots. This is to ensure that the states of the individual robots converge to a common value over time, meaning that they work cooperatively. The design further ensures that this common value can be confined to the origin, such that the robots can cooperatively converge to a stationary point. Recognizing that communication delays are inevitable in real-world scenarios, the proposed distributed controllers are also capable of handling such delays, ensuring that they still allow for state convergence to a common value or zero. The methods are extended beyond mere convergence to enable the robots to form a prescribed formation other than simply agreeing on the same value. The stability of the proposed cooperative control methods is rigorously proven, ensuring their reliability. Finally, simulations are used to confirm the effectiveness of the proposed distributed cooperative control methods [24]. This approach ensures that each robot operates autonomously while coordinating with its neighbors, without the need for a central controller or information from a leader robot.

The paper [25] aims to develop a mathematical model for a system of mobile robots that work together to transport a large object. Specifically, the authors construct a dynamic model for the formation of three mobile robots connected by rotary joints to a transported plate. This model incorporates the principles of analytical mechanics, such as Newton Euler equations, to describe the movement and behavior of the robot formation during transportation tasks. The research addresses real-world challenges such as non-holonomic constraints and the possibility of wheel slips and provides a foundation for creating control algorithms that can compensate for these disturbances. The goal is to create a model that can be implemented in control synthesis, contributing to the efficient and effective design and deployment of cooperative robot systems for complex tasks like large-size transport [25]. Figure 6 shows the system components.

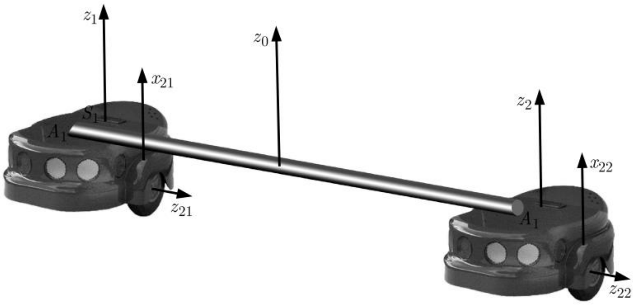

Figure 6. Two Mobile Robots Formation Transporting a Bar [25]

The paper [26] focuses on a decentralized control approach for a multi-robot system in cooperative object transportation. Although it acknowledges other methods like the leader/follower architecture—which could be seen as a more centralized approach—it specifically proposes and develops a decentralized control scheme using deep reinforcement learning. The decentralized control approach equips each robot with a deep Q-network controller, allowing them to learn and make decisions independently of a centralized decision-making unit. This avoids the computational bottleneck that could occur with centralized control when scaling the system. The work does not combine centralized and decentralized methods but rather emphasizes the advantages of the decentralized approach for the task at hand. The main reason for using reinforcement learning, specifically deep reinforcement learning, in the paper is that it allows for the optimization of robot controllers without the need for explicit knowledge of the system dynamics, as developed by [25]. Reinforcement learning algorithms model the reward mechanisms, which indicate the quality of the state resulting from the controller's actions. By using a reward function to guide the optimization, the robots can learn appropriate control strategies through a trial-and-error interaction within the task environment, making it suitable for complex and dynamic tasks like cooperative object transportation. This approach is advantageous because it enables the handling of more general and representative data, which is particularly beneficial when dealing with the complicated dynamics of multi-robot systems [26]. It is also mentioned that the robots involved in cooperative object transportation are assumed to be physically attached to the object, and transport is achieved by either pushing or pulling the object.

In the field of cooperative mobile robotics, various control methods have been developed to effectively coordinate the movement and tasks of multiple robots. Three prominent control methods that have been widely adopted are Virtual Structure, Leader-Follower, and Behavior-based control. The Virtual Structure control method involves the establishment of a virtual structure among the robots, allowing them to maintain a desired formation and perform coordinated tasks. This method enables seamless collaboration and efficient resource utilization in large-scale material transport applications [15][27][28]. The Leader-Follower control method designates one robot as the leader, which navigates and plans the path for the follower robots to follow. This hierarchical approach ensures synchronized movement and effective coordination among the robots, particularly in scenarios where centralized coordination is required [18][29]. The behavior-based control method focuses on endowing each robot with a set of behaviors or rules and allowing them to make decisions based on local sensory information. This decentralized approach enables adaptability and robustness in dynamic environments, making it suitable for complex material transport tasks [30].

The paper [27] integrates the concept of a virtual structure with cooperative control of mobile robotic vehicles. The paper focuses on nonholonomic intelligent vehicles, which are a class of robots with constraints on their movements, such as not being able to move sideways without turning. The cooperative aspect comes into play by employing a consensus approach where all vehicles in the formation agree on certain variables and synchronize their actions accordingly. The novelty of their approach lies in how the formation control problem is structured. The authors propose a formation control strategy that converts the problem into one that involves target tracking and consensus stabilization based on a virtual structure. They establish a formation model based on coordinate transformation, deriving the positions of the following vehicles relative to the leader. This model also involves virtual structures to represent the desired formation pattern. The control laws for the robots are designed using nonholonomic target tracking techniques and leader-follower consensus protocols, which guide the individual vehicles to track their respective virtual points while maintaining the formation. The paper details how the positions of the vehicles are transformed into a coordinate system centered on the leader vehicle, facilitating easier management of the formation. The authors [27] validate their strategy with simulations and real-world experiments. The results show that the vehicles can successfully form and maintain the desired structure, proving the correctness and effectiveness of their approach. The strategy outlined in the paper has several advantages, such as reduced communication overhead among vehicles (since each vehicle is primarily responsible for tracking its virtual point within the structure), a simplified control problem (as the formation control is treated as a target tracking problem), and a fixed structure formation that does not require frequent adjustment or reconfiguration.

In the paper [29] the leader-follower formation control is developed both the leading and following mobile robots and constructed with similar hardware, including a robot base, robot drive, an embedded system using a microcontroller, and a communication system. The mobile robots communicate wirelessly, with the leader robot transmitting instructions to the follower robot. The choice of wireless communication enhances the robots' maneuverability as opposed to being tethered by cables. Different software programs are embedded into each robot's microcontroller. The leader robot's microcontroller contains a program that instructs its movement and sends these movement instructions to the follower. The follower's microcontroller is programmed to receive these instructions and to act on them by imitating the leader's movements. The algorithm dictates that both robots move in a straight line with the front robot acting as the leader. When the leader moves, it transmits information to the follower robot, which receives this information and imitates the leader-robot's movement, maintaining a synchronous linear movement with a maintained distance. The development of the leader-follower system is focused on ensuring that the follower robot can effectively receive and interpret the instructions from the leader robot to maintain formation and distance. This requires careful integration of hardware and software and the implementation of a reliable communication protocol between the robots [29].

The behavior formation control described in the paper [30] is a three-level null space-based control scheme combined with a hierarchical finite state automaton for mission supervision. This method is used to manage multiple unmanned ground vehicle-manipulator (UGVM) systems, which are combinations of a Mecanum-wheeled mobile robot and a robotic manipulator. A model is derived to find the essential control variables for the system, facilitating the coordination between the mobile vehicle and the robotic arm. Controlling these variables enables coordinated movement and manipulation tasks. Basic behaviors for each UGVM are defined and prioritized. These behaviors can be relatively simple tasks that can be dynamically rearranged to cope with different mission requirements and complexities. A critical component that oversees the mission execution by deciding when and how individuals or groups of UGVMs need to switch between various behaviors. The mission supervisor implements this control using a hierarchical finite state automaton, which dictates behavior switches based on system states and external conditions. A control mechanism was developed to enable the UGVMs to follow a desired trajectory while functioning cooperatively within the formation. The controller is designed to ensure that the tracking error of the vehicles and manipulators converges to zero over time, contributing to the system's accuracy and reliability. The behavior formation control system developed in the paper is particularly effective for coordinating multiple robots in formations, which is essential for complex tasks and environments [30]. This method prioritizes distributed control, strong system resilience, and effective obstacle avoidance strategies, which are beneficial for robots operating in dynamic and unpredictable settings.

4. Results and Discussion

Mobile robot platforms are equipped with advanced systems to handle heavy materials efficiently, revolutionizing the transport of large materials in industries such as manufacturing, logistics, and construction. This paper explores their key features, benefits, and impact on productivity and safety. The robotic platform's hardware design, as presented in Figure 1, includes three omnidirectional wheels for versatile movement, two traction wheels for multi-robot object manipulation, a mechanical manipulator with a parallelogram design for lifting objects cooperatively, and modularity to support standalone or multi-robot functionality. This design in [12] meets the requirements for educational and research use in cooperative robotics scenarios where adaptability and effectiveness are crucial.

From [13], the details about the electronic parts are mentioned. The robot platform design includes an acrylic base, 6 V motors with gear reduction, Swedish-type omnidirectional wheels, L298 motor drivers, a DC-DC converter, and a 3000 mAh battery for energy autonomy. Various sensors are included for measuring speed and orientation. The platform uses an Arduino DUE as the main control board to manage sensor information and implement digital pins as interrupt pins for real-time management of sensors and actuators. These features allow for cooperative mobility among the robots, enabling them to work together efficiently in large-scale material transport tasks. Different from [12] where the platform was designed for educational purposes, the design of a multi-wheeled mobile platform incorporates a holonic, homogenous, multi-agent system using Q-learning for precision control for industrial use. The modular architecture features four-wheel steering system with two independent motors each, allowing for flexibility and agility. The maximum manufacturer’s payload is 500 kg, the battery capacity is 52 Ah, and all modules drive independently to enable adaptive navigation considering factors such as energy consumption optimization and optimal trajectory planning.

In the [15], they developed the mobile robot platform with more high technology sensors. The design of the robot focuses on operational simplicity and strong scalability, making it suitable for a wide range of tasks, from building patrols to warehouse logistics. Its ability to autonomously navigate, plan paths, and construct maps is crucial for its intelligence and autonomy. The proposed design addresses limitations seen in other experimental mobile robot platforms by enhancing scalability and expanding functions easily. The mobile robot's ability to autonomously navigate, plan paths, and construct maps is crucial for its intelligence and autonomy. The platform utilizes a full suite of sensors including LiDAR for three-dimensional environmental mapping and an Inertial Measurement Unit for navigation. Additionally, its software system uses the Robot Operating System, allowing the robot to perform complex tasks like real-time path planning and autonomous exploration. Key parameters of the mobile robot platform include a height of 0.75 m, width of 0.53 m, length of 0.86 m, and travel speed of up to 4 m/s.

After discussing the mobile robot platform that is suitable for large-scale material transport in industrial applications, the discussion moves on to the control method, which is crucial for successfully coordinating cooperative transportation by multiple mobile robots. The control methods for large-scale material transport by cooperative robots are complex and crucial. It is essential to identify the most suitable approach to maximize efficiency while minimizing risks and bottlenecks. Safe and efficient transportation methods involve carrying the object on top of the robot, avoiding potential damage. Controlling large-scale material transport by cooperative mobile robots requires coordination of their movements, which can be achieved through centralized or decentralized control methods. Centralized control involves a single controller that coordinates the actions of all the robots, optimizing paths and allocating tasks efficiently. In contrast, decentralized control allows each robot to make autonomous decisions based on its local perception of the environment and tasks at hand. A hybrid approach combining elements of both systems can offer efficient task allocation while maintaining adaptability to dynamic environments. Understanding the strengths and weaknesses of each method is crucial for designing an effective control system tailored to specific factors such as workspace size, task complexity, and the required level of coordination between robots.

The cooperative carrying method for mobile robots described in the study [23] involves a centralized control system using an interval type-2 fuzzy neural controller. This approach enhances coordination between robots during object transport, especially in unknown environments, by handling uncertainties effectively and switching between wall-following and toward-goal behaviors based on the environment and positioning of the robots. Two mobile robots cooperate to carry an object, maintaining a specific distance between each other throughout the task. Different from [23], the study [24] presents a distributed approach to designing a cooperative controller for multiple nonholonomic mobile robots. It involves transforming the system dynamics, creating a distributed controller using information from neighboring robots, and ensuring convergence to a common value over time. The controllers can handle communication delays and enable the formation of prescribed formations. Similar to the strategy used in [24], the research [26] proposes and develops a decentralized control scheme using deep reinforcement learning, equipping each robot with a deep Q-network controller to learn and make decisions independently. The advantage of this approach is avoiding computational bottlenecks when scaling the system. The use of reinforcement learning allows for the optimization of robot controllers without explicit knowledge of the system dynamics, making it suitable for complex tasks like cooperative object transportation in multi-robot systems.

In the field of cooperative mobile robotics, various control methods have been developed to effectively coordinate the movement and tasks of multiple robots. Three prominent control methods that have been widely adopted are Virtual Structure, Leader-Follower, and Behavior-based control. The paper [27] introduces a novel approach to cooperative control of nonholonomic intelligent vehicles using virtual structures. The strategy involves consensus-based formation control and utilizes target tracking and consensus stabilization techniques. The authors validate their approach through simulations and real-world experiments, demonstrating its effectiveness in forming and maintaining the desired formation structure with reduced communication overhead. The paper [29] details the development of leader-follower formation control for mobile robots, which communicate wirelessly. The leader robot transmits instructions to the follower robot, and both are equipped with similar hardware and software programs to maintain synchronous linear movement at a maintained distance. The focus is on integrating hardware and software effectively, along with implementing a reliable communication protocol between the robots. The paper [30] presents a three-level null space-based control scheme combined with a hierarchical finite state automaton for mission supervision, used to manage multiple unmanned ground vehicle-manipulator systems. The method facilitates coordination between the mobile vehicle and the robotic arm through essential control variables, enabling coordinated movement and manipulation tasks while allowing dynamic rearrangement of relatively simple behaviors to cope with different mission requirements and complexities. A critical component oversees mission execution by deciding when individuals or groups of UGVMs need to switch between various behaviors, implemented using a hierarchical finite state automaton based on system states and external conditions. The controller ensures that the tracking error of vehicles and manipulators converges to zero over time, contributing to accuracy and reliability within formations. This approach prioritizes distributed control, strong system resilience, as well as effective obstacle avoidance strategies beneficial for robots operating in dynamic environments.

5. Conclusion

The exploration of cooperative mobile robots for large-scale material transport signifies a pivotal advancement in industrial, manufacturing, logistics, and construction domains. The integration of advanced robotics hardware, sophisticated control strategies, and innovative software systems, as discussed, stands as testimony to the transformative potential of these platforms. Mobile robots equipped with Mecanum wheels and modular scaffolds allow for versatile movement and cooperative manipulation of heavy materials, enhancing operational efficiency and workplace safety. The hierarchical finite state automaton and null space-based control schemes ensure precision in task execution, resilience in dynamic environments, and adaptability to varying mission demands. With the introduction of cutting-edge sensory equipment such as LiDAR and the use of the Robot Operating System for autonomous navigation, the platforms display remarkable self-sufficiency and intelligence.

Moreover, the deployment of centralized and decentralized control methods empowers these robots to collaboratively transport objects safely and with minimal risk, aligning the industrial processes with the advent of Industry 4.0. This research underscores the imperative to continue developing robust and scalable robotic systems, which are crucial to meeting the challenges of modern material transport. As we stride into a future where automation and cooperation among robotic systems become increasingly commonplace, the findings and methodologies presented in this paper provide a foundational blueprint for further innovation and integration of mobile robots in complex, real-world applications.

For future work and challenges in the field of cooperative mobile robots for large-scale material transport, consider addressing the following points. Investigate how the cooperative control strategies perform as the number of robots in the system scales up. Challenges include maintaining communication efficiency, collision avoidance, and synchronization of actions among a larger fleet of robots. Further research could focus on enhancing the robots' ability to operate reliably in highly unstructured and dynamic environments, which could involve unpredictable elements that require real-time adaptation and decision-making. Study how these cooperative robots could better interact with human workers, ensuring safety and seamless collaboration in shared workspaces. Another possible research consideration is energy efficiency. Explore ways to improve the energy efficiency of robots during long missions, which might include better energy management protocols, the use of energy-harvesting technologies, or more efficient route planning.

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