

Control Strategies for Multi-Mobile Robot Systems in Rigid Material Transport: A Structured Narrative Review

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ABSTRACT

This paper presents a structured narrative review of control strategies for multi-mobile robot systems (MMRS) applied to rigid material transport in Industry 4.0 industrial environments. The review covers publications from 2015 to 2023, with 51 sources examined across three thematic categories: mobile robot platform configurations for on-top transport, formation-based coordination and control methods, and IoT/Internet of Robotic Things (IoRT) as enabling infrastructure. The reviewed literature is organised around four main control strategy classes: virtual-structure approaches, leader-follower schemes, consensus-based decentralised control, and learning-based approaches. Each class presents different trade-offs in formation rigidity, communication dependence, scalability, and robustness. The review identifies that rigid material transport constitutes a payload-coupled control problem distinct from general multi-robot navigation, requiring explicit treatment of load stability, wheel slip, nonholonomic motion constraints, and communication latency. Virtual-structure methods currently offer the strongest formation stability guarantees for structured environments, while learning-based decentralised methods provide greater adaptability under uncertainty. IoT/IoRT technologies, particularly UWB localisation and low-latency communication protocols are identified as enabling infrastructure that supports coordination precision rather than as standalone control methods. Future MMRS research should strengthen links between transport control design, payload-aware stability analysis, fault-tolerant coordination, and secure connectivity for both industrial and defence logistics applications.

Keywords: Multi-robot coordination; Cooperative transport; IoT in robotics; Smart manufacturing, Industry 4.0

1. INTRODUCTION

This paper reviews control strategies for multi-mobile robot systems (MMRS) applied to transporting rigid materials in industrial settings, with relevance to defence logistics and autonomous operations. In this review, the term control strategies refers to methods that coordinate multiple mobile robots to move a shared rigid payload while satisfying motion, stability, and safety constraints. This includes formation maintenance, trajectory tracking, obstacle avoidance, inter-robot coordination, and load-related motion constraints. The focus is narrower than general multi-robot coordination because rigid material transport imposes physical coupling between robots through the transported object or supporting platform.

The study is positioned within the context of Industry 4.0, where smart manufacturing demands flexible, autonomous, and fault-tolerant material handling solutions. MMRS offer advantages over single-vehicle systems in terms of scalability, load distribution, and operational redundancy.

Several survey papers have addressed multi-robot coordination in general contexts¹⁻³, and others have examined AGV/AMR deployment in Industry 4.0⁴⁻⁵. However, existing surveys do not specifically synthesise control strategies in the context of cooperative rigid material transport, where

the combination of nonholonomic motion constraints, load-induced dynamics (including wheel slip and tipping), and IoT-based interconnectivity introduces unique design challenges. This review addresses that gap by organising the literature into a taxonomy of control strategy classes and explicitly connecting IoT communication technologies to their effects on coordination performance and stability.

Accordingly, this paper aims to provide a structured narrative review with three specific objectives: (a) to define the control problem in MMRS-based rigid material transport; (b) to classify the main control strategies reported in the literature, including virtual-structure, leader-follower, consensus-based, and learning-based approaches; and (c) to discuss how IoT/IoRT technologies support, but do not replace, the underlying control mechanisms through localisation, communication, and supervisory data exchange.

The paper is organised as follows. Section 2 describes the review methodology. Section 3 presents results covering: (a) mobile robot platforms for on-top rigid load transport, (b) coordination and control strategies for MMRS, and (c) IoT interconnectivity frameworks and their relationship to coordination performance. Section 4 discusses comparative findings, open challenges, and implications for both industrial and defence applications. Section 5 concludes the review.

2. METHODOLOGY

This study adopted a structured narrative review

method to examine control strategies for multi-mobile robot systems (MMRS) in rigid material transport. The review was scoped to literature addressing cooperative transport by two or more mobile robots in industrial or closely related application settings, with emphasis on control, coordination, communication, and payload-handling constraints.

The literature collection was conducted using combinations of keywords including “multi-mobile robot systems,” “multi-robot cooperative transport,” “rigid object transport,” “formation control,” “leader-follower,” “consensus control,” “decentralized control,” “Internet of Robotic Things (IoRT),” and “industrial material handling.” Literature sources included peer-reviewed journal articles, conference proceedings, and selected review papers retrieved from databases including IEEE Xplore, Scopus, and Google Scholar. The review focused on publications from 2015 to 2023 to capture developments relevant to Industry 4.0, though foundational works cited in key papers were included regardless of publication year.

The review prioritised studies that met at least one of the following criteria: (a) explicit treatment of cooperative transport or load-coupled motion, (b) discussion of control or coordination laws for multiple mobile robots, (c) consideration of industrially relevant constraints such as obstacle avoidance, localisation, communication, or fault tolerance, and (d) relevance to rigid material transport or platform-supported payload motion. General papers on Industry 4.0, AGVs/AMRs, or IoT were included only when they provided context or enabling mechanisms directly related to MMRS operation.

Studies were excluded when they focused only on single-robot navigation, generic IoT architectures without robotic coordination implications, or manipulation tasks not related to rigid material transport. The selected works were then analysed qualitatively and grouped into thematic categories covering platform configuration, coordination/control strategy, communication dependence, and enabling IoT infrastructure. Within the coordination category, a secondary taxonomy was applied to classify control strategies as: virtual structure, leader-follower, implicit force-based, consensus-based decentralised, and learning-based decentralised approaches. This taxonomy is used as the basis for comparative analysis in the Discussion section. This approach does not claim the comprehensiveness of a systematic review; rather, it aims to provide a transparent and technically focused synthesis of representative literature.

3. RESULTS

In Industry 4.0, material transport involves automated movement using technologies like conveyors, automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and robotic platforms³⁻⁴. These are supported by sensors, software, and communication tools which are core elements of Industry 4.0⁶⁻⁷.

Smart factories rely on data exchange⁸, IoT⁹, cloud¹⁰, and cyber-physical systems¹¹ to create flexible and automated production¹². These systems use real-time sensors¹³ and RFID¹⁴ to track materials and collect data. IoT enables devices to communicate during material handling¹⁵. Robots can transport items and adjust their paths in real-time¹⁶. Algorithms help reduce delays and improve efficiency. The systems are flexible

and can be reconfigured as needed⁴. Robots improve safety by handling heavy or dangerous materials¹⁷. Integrated handling allows smooth movement across production stages¹⁸.

A key development is the use of AGVs⁵ and AMRs¹⁹⁻²⁰ for autonomous transport. They use smart navigation and obstacle avoidance to move safely in busy factories. Their integration enables efficient autonomous transport. This leads to better productivity, lower costs, and safer workspaces¹⁹. AGVs follow fixed paths guided by tape or lasers²¹. AMRs use sensors and mapping to find routes and avoid obstacles²⁰. AGVs and AMRs show how smart transport tech is growing in factories. Their role is expected to grow as factories need more flexible and intelligent systems²¹.

Vehicle size must match material type, such as using small robots for light loads and larger robots for heavy ones. Using the right size improves safety and efficiency²⁴. Industry 4.0 also supports multi-robot systems that work together like human teams. This marks a major step in improving how factories handle materials. Multi-robot teams bring advantages in collaborative transport¹. These systems adapt better and offer more flexibility. Multiple robots can coordinate their movements and adapt to dynamic factory environments²⁵. They can transport heavy items together²⁶ and respond to real-time changes¹⁶. This adaptability helps production stay on track even when issues arise. Multi-robot systems are also fault-tolerant²⁷. If one fails, others can keep going. This improves system reliability and reduces delays. For rigid material transport,

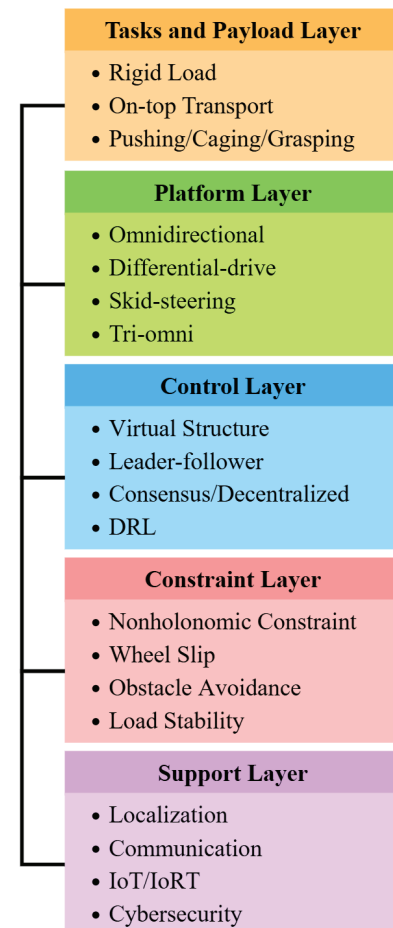


Figure 1. Taxonomy of MMRS control for rigid material transport.

however, the main design problem is not only autonomous mobility but coordinated payload motion. When multiple robots support or transport the same rigid object, the control system must preserve formation geometry, avoid excessive internal forces, maintain payload stability, and satisfy the kinematic constraints of each robot. These requirements distinguish MMRS transport control from general fleet management of independent AGVs or AMRs. Based on the reviewed literature, the MMRS rigid transport problem can be interpreted through interacting layers consisting of payload characteristics, mobile platform selection, coordination strategy, and enabling communication infrastructure. The taxonomy adopted in this review is illustrated in Fig. 1.

In this review, rigid materials refer to payloads whose geometry can be assumed constant during transport, such as boxes, pallets, bins, cylindrical objects, or container-like items. In such cases, the object can impose geometric coupling among the robots, whether through direct contact, grasping, caging, pushing, or platform-supported transport. The associated control problem therefore concerns both robot motion and payload-constrained coordination.

3.1 On Top Object Transport Mobile Robot Platform

From a control perspective, platform selection directly influences the feasible motion model, the severity of wheel slip, the achievable manoeuvrability, and the stability margin of the transported payload. Therefore, the choice between omnidirectional, skid-steering, differential-drive, and other mobile bases is not merely a hardware issue; it affects how coordination laws can be designed and how safely a rigid load can be transported.

To overcome the limitations of traditional approaches, researchers have proposed placing rigid materials directly on top of mobile robot platforms. For on-top transport, stability can be discussed in practical terms through the prevention of payload tipping, sliding, or excessive relative motion between the load and the supporting robots. Although the reviewed papers do not use a single unified stability metric, these issues recur whenever transport involves turning, acceleration, uneven floor conditions, or sudden reconfiguration.

The Savvy robot, features an omnidirectional mobile platform designed for use in confined indoor spaces²⁸. It has a three-layer expandable body, suitable for integrating sensors and actuators, and utilizes Mecanum wheels for omnidirectional movement, offering precise positioning in tight spaces. This configuration enables precise positioning and high maneuverability, particularly in environments with limited space²⁸.

The skid-steering platform consists of a wheeled mobile robot equipped with multiple fixed wheels²⁹. It is commonly used in heavy-duty applications due to its robust design and is controlled by adjusting the speed of wheels on either side. However, this platform may introduce slippage during turns, requiring complex control algorithms.

The differential drive mobile robot employs a straightforward chassis design requiring minimal actuators and sensors³⁰. It maneuvers by independently varying wheel speeds on either side, offering a cost-effective and simple approach for indoor environments.

The tri-omnidirectional wheel platform incorporates three uniquely designed wheels with perpendicular rollers, allowing omnidirectional movement³¹. This design enhances maneuverability in dynamic or obstacle-dense factory settings.

The development of mobile robot platforms for industrial material transport applications has been made to make good use of the mobility and stability of mobile robots with less special equipment. These are the designs of omnidirectional wheels, skid-steering, differential drive, and tri-omnidirectional robots with different abilities to suit various applications.

In general, omnidirectional platforms offer superior manoeuvrability for formation-preserving transport in constrained spaces, whereas skid-steering and differential-drive platforms require greater attention to nonholonomic effects and slip-related disturbances. Thus, platform design should be interpreted as part of the control problem, especially when the payload is carried on top of multiple coordinated robots and stability must be maintained during turning, acceleration, and obstacle-avoidance manoeuvres.

3.2 Coordination and Communication Control Methods of MMRS

Coordination and reliable communication are essential for the efficient operation of multi-robot systems. Effective coordination enables robots to collaborate seamlessly, avoid collisions, and maintain high productivity. Communication supports the exchange of information, collaborative task execution, and real-time adaptation to changes in the environment³².

Based on the reviewed literature, the control strategies for MMRS rigid transport can be grouped into four broad classes: (a) virtual-structure approaches, where the robot team and payload are treated as a unified rigid body; (b) leader-follower approaches, where one robot or the payload trajectory defines the group motion; (c) decentralised or consensus-based approaches, where coordination emerges from local interactions; and (d) learning-based approaches, where coordination policies are acquired from data or trial-and-error interaction. These categories differ in their assumptions about communication, modelling accuracy, scalability, and robustness to uncertainty.

The study³³ presents a mathematical model for cooperative transport using two mobile robots, where dynamic behavior is modeled to avoid wheel slip and ensure accurate control. The robots coordinate closely to transport a shared cylindrical object.

In general, robot formations can be controlled using several approaches, such as virtual structure, behavior-based control, leader-follower models, graph-theoretic methods, and artificial potential fields². These strategies support the maintenance of formation integrity and task synchronization among the robot team.

A coordination strategy for a team of wheeled mobile robots tasked with transporting an object while avoiding obstacles³⁴. The object is placed atop a group of non-holonomic robots that maintain a rigid formation. This virtual structure approach treats the formation as a single entity, requiring the team to establish a specific geometric configuration before the

load is applied. To maintain this formation, the method uses hierarchical quadratic programming to control the robots' positions and orientations while maintaining formation and obstacle avoidance, treating the team of robots and object as a rigid, unified structure.

A cooperative object transport strategy for multi-robot systems with an emphasis on obstacle avoidance³⁵. The method employs the virtual structure paradigm, in which the robot group and the transported object are treated as a single rigid entity. This conceptualization simplifies path planning and formation control. The authors propose a two-layer planning architecture that improves efficiency and facilitates safe navigation around obstacles. This approach allows safe load transportation by a group of robots, even in the presence of obstacles that induce collision risk specifically for robots involved in transportation³⁵.

Virtual-structure approaches are particularly suitable when the transport task requires strong formation rigidity and predictable group geometry. Their main advantage is conceptual simplicity in representing the robot-load system as a single moving structure. However, they usually depend on accurate state estimation and can become more demanding when nonholonomic constraints, obstacle-rich environments, or modelling errors are significant.

In the work by Yufka, *et al.*, a formation-based planning and control framework is proposed for the cooperative transportation of rigid objects by multiple autonomous non-holonomic robots. The strategy treats the object as a virtual leader while the robots act as followers. A smooth trajectory is generated by maintaining a consistent distance and orientation relative to the leader. The system employs asymptotic tracking control to ensure stable and coordinated movement throughout the transport task. In this approach, the transported object acts as a virtual leader, and the robots maintain formation by adjusting their trajectories based on the object's movement, which was validated through simulation and real-world application. The proposed system's effectivity was verified through simulation and real application using the mobile robot Pioneer P3³⁶.

Chao-Wei Lin proposed a hierarchical coordination control framework for multi-robot systems based on a leader-follower scheme with region-based tracking. In this approach, only the lead robot has access to the desired trajectory, which is defined implicitly. The follower robot then tracks the path indirectly by observing the leader's movement within a predefined boundary. This strategy reduces communication requirements and offers greater flexibility compared to traditional virtual structure and behavior-based methods³⁷.

Leader-follower approaches reduce coordination complexity by assigning trajectory authority to one robot or to a virtual leader associated with the payload. This can lower communication requirements, but the overall transport performance may become sensitive to leader behaviour, tracking errors, and the propagation of motion disturbances to the follower robots.

The coordination strategy³⁸ eliminates the need for explicit communication. Instead, it adopts a leader-follower model in which the leader robot directs the overall movement by applying a controlled force to the object. The follower robot detects this force locally at the point of contact and

synchronizes its own force accordingly. This implicit communication mechanism supports system scalability and simplifies reconfiguration. Robots can be added or removed by connecting or detaching them from the object, without requiring updates to communication protocols or control software. This approach is particularly useful for cooperative manipulation of heavy objects.

The authors³⁹ propose a decentralized control strategy for multi-agent systems with the objective of achieving predefined geometric formations, such as a rectangular lattice. The control algorithm is based on the concept of information consensus, which relies solely on local data and does not require a fixed communication graph or a designated leader. This approach enables agents to maintain their formation while navigating, offering a flexible alternative to leader-follower models and biologically inspired behavior-based methods³⁹.

Communication-light and decentralised strategies improve scalability because they rely less on global information. In cooperative transport, their practical success depends on whether local sensing or contact interaction provides sufficient information to preserve payload stability and coordinated motion, especially during directional changes or obstacle avoidance.

The study⁴⁰ introduces a decentralized coordination strategy using deep reinforcement learning for collaborative object transport. Each robot is equipped with a decentralized deep Q-network controller that enables learning through trial-and-error interactions within the environment. This method fosters cooperation and provides robustness under uncertainty, eliminating the need for centralized control or full knowledge of the system dynamics. Each robot adapts its strategy independently while contributing to the collective task of transporting large objects and maintaining formation. Curriculum-based deep reinforcement learning has also been applied to cooperative object transport, demonstrating progressive task learning strategies⁴⁰.

Learning-based approaches offer flexibility in uncertain environments and can reduce dependence on precise analytical models. Nevertheless, their adoption in rigid industrial transport still requires careful consideration of training conditions, safety guarantees, interpretability, and transfer from simulation to hardware.

Across these control categories, several technical issues repeatedly shape MMRS transport performance. First, payload stability must be maintained during acceleration, turning, and stopping, particularly in on-top transport configurations where sliding or tipping may occur. Second, wheel slip can degrade trajectory tracking and alter the intended force distribution among robots, especially for skid-steering or heavily loaded platforms. Third, nonholonomic constraints limit feasible motion and therefore influence formation geometry, path planning, and controller structure. Fourth, communication architecture affects whether coordination can remain stable under latency, packet loss, or partial observability.

3.3 IoT/IoRT as Enabling Infrastructure for MMRS Control

In the context of this review, IoT and IoRT are treated as enabling infrastructure for MMRS control rather than

as control strategies by themselves. Their relevance lies in providing localisation, state sharing, supervisory monitoring, and communication support that can improve the implementation of cooperative transport controllers. Therefore, IoT-related technologies are discussed here only to the extent that they influence control performance, coordination reliability, or deployment feasibility. MMRS are typically equipped with sensors, cameras, and other hardware to enable autonomous perception and decision-making. The integration of IoT technologies further enhances their capabilities by improving communication, data exchange, and coordination among multiple robots⁴². This integration facilitates efficient cooperation among robots working toward shared objectives. In warehouse settings, for instance, IoT-enabled mobile robots can communicate to optimize workflow and avoid collisions, enhancing both efficiency and safety. Furthermore, real-time data collection through IoT supports predictive maintenance and performance optimization. When connected to cloud-based platforms, these robots can process and analyze data to support continuous improvement. This interconnected framework is known as the Internet of Robotic Things (IoRT), which merges IoT and robotics to establish a dynamic ecosystem of smart, interconnected robots⁴³. This includes the integration of sensors, actuators, cloud services, and communication interfaces enabling real-time cooperation and autonomy among robot units.

Kamilaris, *et al.* explore how the Web of Things (WoT) can be integrated with robotics to advance the concept of the Web of Robotic Things⁴⁴. Their conceptual model outlines interactions between devices, web platforms, and robotic control systems to form a seamless digital-physical interface. Vermesan, *et al.* categorizes IoRT applications into distinct domains. These domains illustrate how robotic systems can be deployed across various sectors, from manufacturing to healthcare, driven by intelligent sensing and connectivity⁴⁵.

The integration of IoT and Industrial IoT (IIoT) technologies with robotics significantly enhances capabilities in sensing, actuation, cognition, computation, and connectivity. This allows robotic systems to manage complex and dynamic real-world tasks⁴⁵. IoT also provides a foundational framework for collaboration between robots, other IoT-enabled devices, and human operators. This cooperation requires the convergence of several technologies, including IoT, AI, smart connectivity, and dependable frameworks, to address critical challenges such as interoperability, latency, and cybersecurity⁴⁵.

Krupitzer, *et al.* designed the RoCoSys framework. RoCoSys is an advanced framework for coordinating mobile IoT devices, like robots. This design uses a structured approach based on MAPE control: monitoring, analyzing, planning, and executing functions⁴⁶. This system continuously monitors the robot and its operation environment while analyzing data to assess current conditions and identify optimal chances. This allows independent coordination where the robot independently suits itself with surrounding changes or various objectives. Especially with the LEGO Mindstorm robot, which is used to demonstrate autonomous fleet and smart logistic operation.

Another study observes how IoT can increase supervision systems for mobile applications, such as robots and autonomous vehicles. It can be imagined as a system where a vehicle's

sensors are connected through IoT to create an expanded perception system. The use of this IoT helps to solve line-of-sight constraints by using wireless network-based perception, which does not need direct visibility and can travel around obstacles⁴⁷. This research objective is to use high-update frequency potential in 5G networks in the future for real-time applications that are important in dynamic scenarios. However, integrating IoT into this system also presents a challenge related to the analysis and interpretation of a large amount of data in critical services like autonomous driving. To handle these things, the proposed solution involves merging IoT with AI to analyze data efficiently and make smart predictions to increase performance and safety⁴⁷.

In the robot formation study by Guan, *et al.*, an IoT system was designed to enable efficient and quick information acquisition and transmission, this is significant for controlling the formation of robot collaboration. With IoT technology, real-time detection from various external surroundings, robots' trajectory data collection, and feedback mechanisms to control cooperative movement from several robots become possible. This improvement contributes to accuracy, efficiency, and adaptability in handling robot formation in complex and dynamic environments⁴⁸. IoT technology allows mobile robots to communicate and exchange information in real-time. The described IoT-based formation control framework allows robots to exchange trajectory data, sense external environments in real-time, and coordinate movement efficiently without centralized control, enabling highly adaptive and responsive robotic swarms.

The IoT development⁴⁹ discussed focuses on providing high-precision service of location and allows the creation of autonomous systems, especially with ultra-wideband (UWB) technology. While integrated with UWB technology, IoT devices can use localization abilities precisely required for various applications, including autonomous robotics and industrial IoT systems. UWB improves IoT applications that allow distance measurement and wireless-determined position accurately and robustly in surroundings where the GPS traditional systems may be unreliable.

IoT plays an important role in increasing control and trajectory tracking performances of non-holonomic mobile robots⁵⁰. The aspects of IoT technology involve the use of sensors and electronic tags that are installed in the robot for collecting data. It helps robots to perceive the environment and communicate with the other end using the internet. That research paper also refers to a wireless sensor network technology: ZigBee. ZigBee is said to connect numerous devices wirelessly in the network and to enable the communication and interaction of sensors and actuators embedded in the robot. Connecting the machine vision system to IoT allows strong network functionality, like object detection using the camera, which can improve local node intelligence (robots). This reduces the processing load in the central server and contributes to distributed control systems becoming more efficient. By embedded sensors, the robot gets both raw data and high interpretation, which is significant for the decision-making process. This ability makes robots more autonomous and allows them to interact and collaborate efficiently.

By utilizing intelligent perception and data collection by a sensor network, the system can make the assessment and timely decision-making. This also involves the issuance of control instructions to ensure that several robots can complete tasks with safety and efficiency. The reviewed literature proposed a trajectory tracking method that combines a backpropagation neural network extended with neuro-fuzzy, and it is called fuzzy-BPNN. This method, validated through simulation, shows improvement in speed and tracking accuracy. This research combines data from several sensors to enrich the availability of information in the control robot's trajectory. By image enhancement technology, the target image is processed so that it is more effective for the robot system, assists in proper and efficient navigation, and finishes tasks. Overall, this research utilizing IoT to make robot trajectory tracking more accurate and efficient depends on an advanced sensor network and improved processing ability facilitated by IoT technology⁵⁰.

In previous studies, IoT technology has been used to exchange information between mobile robots. Different from those studies, the study uses IoT for a hospital logistics system that is equipped with autonomous mobile robots and IoT modules⁵¹. The robots were used for tasks like food and medical supplies delivery to a patient, especially during the COVID-19 pandemic. The IoT platform allows health officers to monitor and control robots effectively through a web application, performing care to patients while complying with the infection control protocols. Although hospital logistics differs from industrial rigid-load transport, it illustrates how IoT-connected mobile robots can be supervised through a common platform. In this paper, such examples are considered peripheral and are used only to show deployment-level coordination infrastructure rather than core payload-coupled transport control.

The reviewed IoT technologies have direct implications for MMRS coordination performance in rigid transport tasks. UWB-based localisation⁴⁹ can achieve sub-decimeter positioning accuracy, which is critical for maintaining formation geometry when robots jointly support a rigid load: positioning errors exceeding the geometric tolerance of the load attachment points will induce internal forces that may destabilise the formation or cause wheel slip. ZigBee-based communication networks⁵⁰, while suitable for low-bandwidth sensor data, introduce latency that constrains the update rate of formation control loops; for fast-moving platforms, this latency may cause formation error accumulation. The 5G-enabled IoT framework⁴⁷ addresses this by enabling low-latency, high-bandwidth communication suitable for real-time formation control in dynamic environments. Conversely, as connectivity increases, cybersecurity vulnerabilities also expand, as noted in the context of IIoT integration⁴⁵. These tradeoffs between localisation precision, communication latency, bandwidth, and security represent system-level design constraints that must be considered alongside the choice of control strategy for MMRS rigid transport applications.

4. DISCUSSIONS

The reviewed studies collectively show that MMRS performance in rigid material transport depends on the

interaction between platform design, coordination law, payload condition, and communication support. Therefore, no single control strategy is universally optimal; instead, the suitability of a method depends on whether the task prioritises formation rigidity, low communication dependence, adaptability, or implementation simplicity.

The comparative analysis (Table 1) reveals that no single method satisfies all requirements for industrial rigid transport simultaneously. Virtual structure methods provide the highest formation stability guarantees and most explicit handling of nonholonomic constraints, making them well-suited for structured factory environments with predictable paths. However, their reliance on centralised coordination limits scalability and increases vulnerability to single-point failures. Leader-follower schemes offer a middle ground, reducing communication overhead while maintaining reasonable formation integrity, though their performance degrades when the leader's trajectory involves sharp turns that induce wheel slip in follower robots. Implicit force-based coordination³⁸ eliminates communication infrastructure requirements entirely, offering high fault tolerance and easy reconfiguration, but provides limited control over formation geometry during dynamic manoeuvres. Consensus-based and deep RL methods offer the highest scalability and adaptability, but their stability guarantees under load-induced disturbances remain an open research question.

The fault-tolerance of MMRS is particularly relevant in industrial and defence contexts where uninterrupted payload delivery is critical. If one robot fails during transport, the remaining robots can sustain the coordinated motion and complete the task.

Unlike traditional fixed-route factory transport, MMRS offer greater flexibility through their distributed design and coordinated movement. The reviewed literature indicates that MMRS provide stability advantages over single-vehicle systems, partly due to their distributed load support and lower effective centre of gravity during transport. This is vital in smart factories to avoid downtime or accidents.

Factories are increasingly replacing fixed conveyors with more flexible MMRS configurations. Despite these benefits, coordinating robot movements remains challenging, particularly in maintaining load stability along complex paths. A central issue that deserves greater emphasis is payload-aware stability. In rigid transport, instability may arise not only from path error but also from payload sliding, tipping tendency, uneven load distribution, or wheel slip under acceleration and turning. These effects are closely related to robot kinematics and floor-contact conditions. For this reason, future MMRS studies should more explicitly connect control design with payload stability analysis and slip-resilient motion control. More advanced path planning and communication protocols are needed.

Future MMRS development would benefit from greater flexibility in handling objects of various dimensions and geometries. Current platform designs and gripping mechanisms tend to restrict the range of transportable materials, and modular or adaptive gripping technologies could help address this limitation. The reviewed literature consistently indicates

that coordination and communication are critical to MMRS operation in Industry 4.0 contexts.

Across the surveyed studies, robots have demonstrated the ability to smoothly transport objects in environments with space constraints and dynamic obstacles, provided that effective synchronisation is achieved. Various control approaches, including virtual structure, behavior-based, leader-follower, graph-based, and artificial potential field methods, have been reviewed. Of these methods, the virtual structure method has so far shown promise because it maintains formation and stability during transport tasks while simplifying path planning and facilitating obstacle avoidance. This approach considers the group of robots as an entity for achieving its objectives.

Virtual-structure methods appear advantageous when strict geometric coordination and unified motion are required, but they rely on reliable modelling and state estimation. Leader-follower methods reduce coordination complexity, although they may be sensitive to leader disturbance and follower tracking quality. Decentralised and consensus-based methods offer scalability and robustness to single-point failure, but their effectiveness depends on the sufficiency of local sensing and interaction rules. Learning-based methods are promising for uncertain or changing environments, yet they still require stronger validation for safety-critical industrial transport.

The reviewed methods, while effective in their respective contexts, leave room for further improvement. Advanced control algorithms and real-time data exchange strongly demand computational resources and network infrastructure. As tasks become more complex, more advanced communication protocols are needed to manage high-throughput and low-latency requirements.

Hierarchical control structures play an important role in managing competing task objectives. The hierarchical quadratic programming approach³⁴, for example, prioritises formation maintenance over obstacle avoidance, allowing the system to handle both objectives simultaneously. That underlines the necessity of control methods that can adapt to different operational situations, ranging from routine material transport to emergency collision avoidance tasks.

A recurring concern in the reviewed literature is wheel slip during transport. Longitudinal or lateral slipping can cause instability and endanger the payload, requiring control algorithms that respond quickly to such disturbances.

Future research efforts should concentrate on MMRS fault-tolerant cooperative control mechanism design, with autonomous error detection, diagnosis, and recovery with minimal human intervention. Innovation in adaptive gripping technologies and modular platforms able to automatically adjust to load geometry would extend MMRS applicability to materials of various dimensions.

The applicability of MMRS to defence logistics deserves specific attention given the scope of this journal. Coordinated multi-robot transport of rigid military payloads, such as munitions, equipment crates, or casualty evacuation platforms, shares the same fundamental control challenges as industrial transport: formation stability, wheel slip management under varied terrain, and communication reliability. However, defence environments introduce additional constraints including

operation in GPS-denied or communication-contested environments, the requirement for silent operation (minimising RF emissions), and the need for rapid reconfiguration after platform attrition. The implicit force-based coordination approach³⁸ is particularly relevant to defence scenarios because it requires no wireless communication, reducing electromagnetic signature. Similarly, deep RL-based decentralised control⁴⁰ offers potential for operation in degraded communication environments. UWB localisation⁴⁹ provides an alternative to GPS for indoor or urban canyon environments.

The role of IoT/IoRT in this context is mainly infrastructural. The literature suggests that connectivity can improve localisation, supervisory awareness, data sharing, and predictive maintenance. However, these benefits contribute to MMRS performance only when the underlying control architecture can tolerate latency, communication loss, and cybersecurity risks. Thus, IoT integration should be interpreted as a support layer for control implementation rather than a substitute for transport-control design.

Growing device interconnectivity opens new challenges, mainly in security and data privacy. As more devices connect, so does the potential for cyber threats that might disrupt manufacturing operations. Therefore, there is a need for appropriate security frameworks and trustworthiness protocols that will protect them from such vulnerabilities. Ensuring safety and security within these connected devices is therefore a priority for future IoRT deployments in manufacturing.

The reviewed literature suggests that challenges such as interoperability, latency, and security can be partially addressed through the integration of IoT with AI and intelligent connectivity⁴⁵. MMRS needs more research into these converging technologies if there is to be an improvement in decision-making and autonomous capability.

Although most reviewed studies are situated in industrial environments, similar coordination principles may be transferable to defence logistics, such as cooperative movement of supplies in hazardous areas. In the present review, however, this implication should be regarded as prospective rather than extensively validated, because the surveyed evidence remains predominantly industrial.

5. CONCLUSION

This paper presented a structured narrative review of control strategies for multi-mobile robot systems in rigid material transport. The review showed that the most relevant control classes in the surveyed literature are virtual-structure, leader-follower, decentralised/consensus-based, and learning-based approaches, each involving different trade-offs in formation rigidity, communication dependence, scalability, and robustness. The analysis highlighted that rigid material transport should be treated as a payload-coupled control problem rather than as general multi-robot navigation alone.

Across the reviewed studies, recurring technical challenges include payload stability during motion, wheel slip, nonholonomic constraints, communication latency, and the practical integration of localisation and sensing infrastructure. IoT/IoRT technologies can strengthen MMRS deployment by supporting data exchange, supervision, and positioning,

Table 1. Comparative summary of MMRS control strategies for rigid material transport

Control strategy	Formation stability	Wheel slip handling	Nonholonomic constraint	Communication required	Scalability	Key Ref.
Virtual structure	High	Partial	Explicit	High (centralised)	Low	(34,35)
Leader-follower	Medium	Low	Moderate	Medium	Medium	(36,37)
Implicit force-based	Medium	Low	Low	None	High	(38)
Consensus-based	Medium	Not addressed	Moderate	Low (local only)	High	(39)
Deep RL	Variable	Implicit	Implicit	Low	High	(40,41)

but they do not replace the need for payload-aware and fault-tolerant control design. Future research should therefore focus on stronger links between transport control, stability analysis, secure connectivity, and real-world validation in industrial settings, while also exploring transfer to defence logistics scenarios.

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