МОДЕЛІ БЕЗПЕЧНОЇ ВЗАЄМОДІЇ АВТОМАТИЗОВАНОГО ТРАНСПОРТУ ТА ПЕРСОНАЛУ В СУЧАСНИХ ІНТЕЛЕКТУАЛЬНИХ СКЛАДСЬКИХ СИСТЕМАХ

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Анотація: Дана стаття присвячена аналізу проблематики безпечної взаємодії автоматизованого транспорту (AGV/AMR) з персоналом у сучасних складських системах. Проведено аналіз основних ризиків, пов’язаних із експлуатацією автономних візків у змішаному середовищі, та наведено теоретичні підходи до моделювання безпечної поведінки роботизованого транспорту. Описано концепції зон безпеки, протоколи уповільнення й аварійної зупинки, а також сучасні сенсорні рішення для виявлення людини. Обґрунтовано важливість поєднання технічних і організаційних заходів задля зниження травматизму та підвищення надійності складських процесів.

Ключові слова: автоматизований транспорт, складські системи, безпечна взаємодія, AGV, зони безпеки.

MODELS OF SAFE INTERACTION BETWEEN AUTOMATED TRANSPORT AND PERSONNEL IN MODERN INTELLIGENT WAREHOUSE SYSTEMS

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***Annotation*:** This article is devoted to analyzing the issues of safe interaction between automated transport (AGV/AMR) and personnel in modern warehouse systems. An analysis of the main risks associated with the operation of autonomous trucks in a mixed environment is carried out, and theoretical approaches to modeling the safe behavior of robotic transport are presented. The concepts of safety zones, deceleration and emergency stop protocols, as well as modern sensor solutions for human detection are described. The importance of combining technical and organizational measures to reduce injuries and increase the reliability of warehouse processes is substantiated.

Key words: automated transport, warehouse systems, safe interaction, AGV, safety zones.

Industry 4.0 is based on process digitalization, cyber-physical systems, IoT connectivity, and real-time data processing. This is changing the approach to internal logistics. The warehouse is no longer “mechanical.” It is becoming a data-driven system.

AGVs/AMRs in warehouse systems - are not isolated robots. They form a fleet that shares space, charging resources, and “bottlenecks” such as aisles, gates, and elevators. Without coordinated control, downtime, path conflicts, queues, and deadlock situations arise. Reviews of AGV control systems identify dispatching, routing, collision avoidance, and battery management as key tasks. This confirms the critical importance of architecture at the fleet level, not just at the level of a single robot.

Compatibility creates additional pressure. Warehouse ecosystems increasingly combine different types of transport robots and infrastructure. Hence the need for standards and reference architectures. RAMI 4.0 defines the structure for describing Industry 4.0 components by layers, levels, and lifecycle. This is useful for the systematic design of AGV integration into a facility.

In terms of safety and standardization, AGVs and AMRs are often considered “driverless industrial trucks.” They require safety requirements and verification methods. This directly underscores that fleet management must be linked to operating modes, zones of interaction with people, and risk control.

Structurally, an AGV fleet performs repetitive transport cycles between “nodes.” Efficiency here depends on four factors: task allocation, traffic management in shared space, charge management, and integration with the task source. In Industry 4.0, these processes must be transparent and data-driven, including real-time events and statuses.

Virtually any fleet management system has three levels of functions:

1. Local: navigation, localization, obstacle avoidance;
2. Site: dispatching, traffic, energy, zone rules;
3. Enterprise: task integration, KPIs, planning.

RAMI 4.0 proposes thinking in layers and aligning data/interfaces between adjacent layers. This suggests that “fleet control” should be separated from the business layer and the physical layer, but with defined event flows.

Centralized architecture. The key idea is that a single “fleet/master control” forms a task queue and assigns tasks to robots. It also maintains a global map/graph and traffic rules. This approach scales well administratively. It is easier to maintain. It is easier to integrate with WMS/MES/ERP via a single interface.

A practical hallmark of the centralized approach is the presence of “job queuing and dispatch,” “traffic management,” centralized map control, and a “single point of integration.” This is explicitly described in industrial solutions for managing fleets of mobile robots, such as Enterprise Manager/ARAMCentral.

Strengths. Transparency. A unified priority policy. It is easier to ensure data consistency. It is easier to build unified analytics.

Weaknesses. Bottleneck. High dependence on the availability of the server, network, and message brokers. Risk of “cascading degradation” in the event of a central component failure. Cyber security requirements for the central node also increase.

Decentralized architecture. Coordination is moved closer to the robots. Decisions regarding trajectories, priorities, and conflict resolution are made locally or in a group setting. Communication is often structured as “multi-agent” with rule coordination.

Advantage: resilience. The failure of a single node does not halt the entire fleet. Dependence on central infrastructure is reduced. Flexibility in a dynamic environment increases.

Disadvantage: complexity of guarantees. It is harder to prove global optimality. It is harder to ensure fairness and predictability. The cost of interaction errors increases, especially in “bottlenecks” and when moving alongside people. In the classical literature, the tasks of dispatching, routing, and collision avoidance are fundamental to AGV control. Transferring these tasks to a decentralized mode increases the demands on coordination protocols.

Hybrid architecture. This is the dominant practical compromise. The control center is responsible for “what” and “when.” The robots are responsible for “how exactly.” That is, the control center assigns missions, priorities, and zone and traffic rules. The robot performs navigation, obstacle avoidance, and precise positioning locally.

Industrial fleet management products explicitly support centralized control, dynamic task assignment, traffic management, and integration with WMS/MES/ERP via API. This is a typical description of the hybrid approach, where the “fleet manager” defines policy and dispatching, while the robot’s autonomy ensures execution in the real environment.

A distinct advantage of the hybrid approach is compatibility. A standardized interface between "master control" and robots allows for the creation of a multi-vendor fleet. VDA 5050 defines precisely this type of interaction. The standard describes the exchange of orders and statuses between the master control and AGVs. It is based on MQTT and JSON. It also sets out the following goals: reduced integration time, "plug & play," parallel operation of different manufacturers, and coordinated traffic management.

Figure 1 shows the "fleet control → MQTT broker → mobile robot" pattern with typical topics "/order" and "/state." This is convenient for Industry 4.0 because it aligns with event-driven integration and provides a unified channel for telemetry and commands.

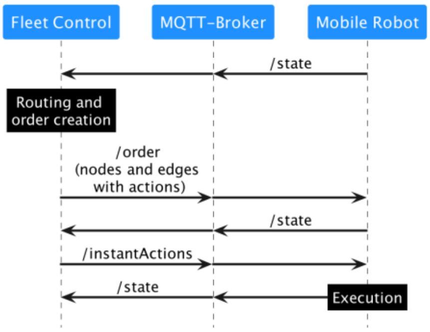

Figure 1 – Information Flow Structure

A "middleware" approach is used to integrate different fleets and infrastructure. OpenRMF is described as a modular framework (Fig. 2). It provides centralized functions. These include task queuing, conflict-free resource scheduling, and tools for building fleet adapters. This supports a hybrid "multiple fleets and shared building resources" scenario.

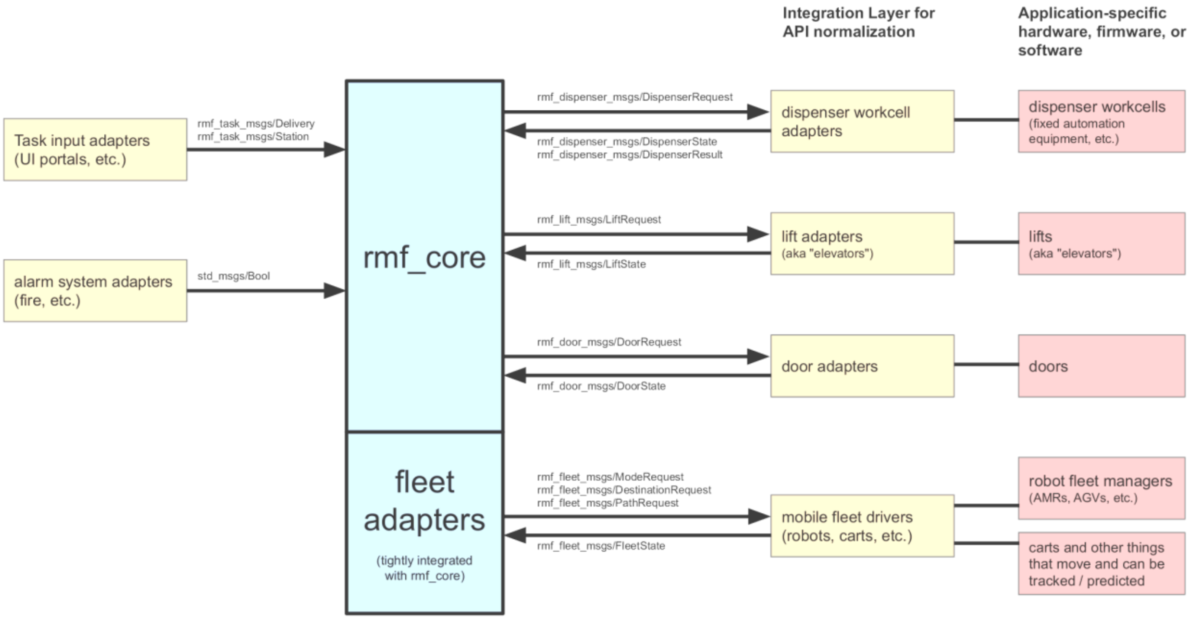

Figure 2 – General structure of the OpenRMF deployment

A comparative analysis was performed in Table 1. The table focused on warehouse systems featuring shared traffic areas, periodic "bottlenecks," and Industry 4.0 integration requirements.

Table 1 – Comparison of AGV Fleet Management System Architectures

Criterion	**Centralized**	**Decentralized**	**Hybrid**
Decision-making	The center determines routes/queues/rules	Decisions are distributed among robots/agents	The center determines policy and mission allocation; the robot executes them locally
Fleet scaling	Works well up to a certain point, then bottlenecks at the center	Natural scaling, but more complex coordination	Scales well with standardized interfaces and brokers
Fault tolerance	Low without redundancy	Higher, no single point of failure	Higher than centralized systems with proper degradation and failover
Traffic consistency	High, if the center “sees” all resources	Difficult to guarantee global consistency	High for “rules,” local autonomy for “exceptions”
Criterion	Centralized	Decentralized	Hybrid
Response time to local failures	Network/center delays	Minimal	Minimal, with the center adjusting policy
Integration with WMS/MES /ERP	Simple (single point)	More complex (requires a “gateway”)	Usually simple: one hub + API/events
Multi-vendor	Often limited by proprietary systems	Potentially high, but standards are needed	Works best with standards like VDA 5050
Maintenance costs	Lower at the start	Higher due to the complexity of the rules	Average: more complex than centralized, but manageable

Cybersecurity and lifecycle management should be considered separately. In Industry 4.0, this becomes an architectural requirement. For example, industrial fleet management solutions may offer event-driven integration, APIs for ERP/WMS/MES, and access/audit mechanisms as part of the product. This influences the choice of architecture in favor of a hybrid approach, where the “hub” serves as a managed integration node.

CONCLUSIONS. The architecture of an AGV fleet management system determines not only performance but also risk management and integration costs. For Industry 4.0 warehouse systems, a hybrid approach is the most practical. It allows robots to retain local autonomy. It preserves centralized dispatching and traffic management mechanisms. This is precisely how “master/fleet control” functions are described in standardized interfaces and industrial products.

Compatibility standards significantly lower the “vendor lock-in” barrier. VDA 5050 formalizes the exchange between master control and AGVs via MQTT/JSON and supports the parallel operation of equipment from different manufacturers. This is directly linked to Industry 4.0 requirements for horizontal integration and real-time data management.

Reference models such as RAMI 4.0 serve as a “roadmap” for mapping fleet management functions across the business layer, functional layer, and communication mechanisms. This reduces the complexity of integration and allows the system to be broken down into modules with clear interfaces.

ЛІТЕРАТУРА

1. Le-Anh, T., & De Koster, M. B. M. (2006). A review of design and control of automated guided vehicle systems. European Journal of Operational Research, 171(1), 1–23.

2. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications, and open research issues. Journal of Industrial Information Integration, 6, 1–10.

3. ZVEI / VDI (GMA). (2015). Reference Architecture Model Industrie 4.0 (RAMI 4.0) (GMA Status Report).

4. VDA. (2025). VDA 5050: Interface for communication between automated guided vehicles (AGV) and a master control (Version 2.1.0).

5. International Organization for Standardization. (2020). ISO 3691-4: Industrial trucks — Safety requirements and verification — Part 4: Driverless industrial trucks and their systems.

6. Mobile Industrial Robots. (2026). MiR Fleet (fleet management software).

7. OMRON. (2017). Mobile Robot Software Suite User's Guide (Enterprise Manager / ARAMCentral).

8. Open Source Robotics Corporation. (2021). OpenRMF documentation: Overview and integration diagram.

9. Industry 5.0 та колаборативна робототехніка: динамічний опис навколишнього середовища роботів-маніпуляторів з використанням мови Python: монографія / І. Ш. Невлюдов, В. В. Євсєєв, С. С. Максимова. – Харків : Видавництво Іванченка І. С., 2026. – 279 с. https://doi.org/10.30837/978-617-8332-95-2

10. Nevliudov , I. ., Omarov , M. ., Yevsieiev , V. ., Maksymova , S. ., & Jabrayilzade , E. . (2026). MATHEMATICAL MODELING OF TRAJECTORIES CONSTRUCTION, MOVEMENT OF THE GRIPPING DEVICE OF A COLLABORATIVE ROBOT. Advanced Information Systems, 10(1), 11–20. https://doi.org/10.20998/2522-9052.2026.1.02

11. Yevsieiev, V. Comparative Analysis of the Characteristics of Mobile Robots and Collaboration Robots Within INDUSTRY 5.0. / V. Yevsieiev, D. Gurin // Sectoral research XXI : characteristics and features : collection of scientific papers "SCIENTIA" with proceedings of the VI International Scientific and Theoretical Conference, September 8, 2023. - Chicago : European Scientific Platform, 2023. - P. 92-94.

12. Automated Monitoring and Visualization System in Production / V. Lyashenko, Abu-Jassar Amer Tahseen, V. Yevsieiev, S. Maksymova // Int. Res. J. Multidiscip. Technovation, 5(6), 09-18. https://doi.org/10.54392/irjmt2362

13. Gurin, D., Yevsieiev, V., Maksymova, S., & Alkhalaileh, A. (2024). MobileNetv2 Neural Network Model for Human Recognition and Identification in the Working Area of a Collaborative Robot. Multidisciplinary Journal of Science and Technology, 4(8), 5-12.

14. Yevsieiev, V., Gurin, D., Kulish, S., & Voloshyn, Y. (2025). Development of a partially supervised Markov decision-making model for a 3-link collaborative robot-manipulator. Radioelectronic and Computer Systems, 2025(4), 83-94. doi:https://doi.org/10.32620/reks.2025.4.06

15. Невлюдов, І., Клименко, О., Євсєєв, В., & Максимова, С. (2025). IMPROVEMENT OF THE ENCODING INFORMATION METHOD FOR PHARMACEUTICAL PRODUCTS QR-CODES DURING SORTING ON A ROBOTIC CONVEYOR LINE. Вісник Національного технічного університету «ХПІ». Серія: Технології в машинобудуванні, (1 (11)), 128-134. https://doi.org/10.20998/2079-004X.2025.1(11).15

16. Yevsieiev V. Digital Twins of Collaborative Robotic Systems for Decision Support in Emergency Situations / V. Yevsieiev, S. Svetlana // Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations (ICSTRO-2026) : Proceedings of I-st All-Ukrainian Conference, February 12-23, 2026. – Kharkiv, 2026. - P. 153-156.