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Risk assessment and safety strategies for industrial robots use in transport

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The development of robotic logistics processes is placing increasing emphasis on the operational safety of industrial robots in goods transport. Mobile robots, such as AGVs (Automated Guided Vehicles) and AMRs (Autonomous Mobile Robots), play a significant role in streamlining internal transport, but their integration with internal infrastructure carries the risk of collisions, breakdowns, and operational disruptions. This article presents the fundamental safety aspects of transport robots, with particular emphasis on applicable standards and technical systems based on sensors, LiDAR (Light Detection and Ranging), and vision systems. Selected industrial implementations are also discussed, demonstrating the need for a comprehensive approach to designing safety zones and traffic management in robotic warehouses. The aim of this paper is to highlight the importance of safety aspects in the context of the growing use of robots in logistics and internal transport and to identify directions for further development in this area.

Key words: *industrial mobile robots, autonomous vehicles, internal transport, operational safety, risk assessment*

1. Introduction

The dynamic development of industrial process automation is a key aspect of the modern economy, underpinning the Industry 4.0 concept [20]. Autonomous systems and mobile robots occupy a special place in this concept, not only streamlining material flow within a plant but also contributing to increased production efficiency, quality, and occupational safety. However, with their widespread use, there is a need to develop and apply precise standards governing their design, implementation, and operation. One of the most important documents in this regard is the PN-EN ISO 3691-4:2024-01 standard, which specifies safety requirements for industrial automated guided vehicles (AGVs) and mobile robots (AMRs) intended for operation in environments where human interaction occurs. This standard defines both technical parameters and organizational procedures to minimize the risks associated with the operation of autonomous devices [6]. It addresses issues such as speed limits, designing highly reliable control systems, using obstacle detection systems, and implementing mechanisms for human-machine communication. Applying the standard's guidelines in industrial practice enables compliance with European and national laws and contributes to a culture of safety in companies implementing mobile robotics solutions [19].

Fig. 1. The prototype of an autonomous mobile robot under the transport trolley [28]

2. Safety of mobile robots used in transport

2.1. Safety characteristics and requirements

Industrial robots used in internal transport can be characterized as complex mechatronic systems, combining mechanical, sensory, control and IT functions [28]. Their main task is to implement automated load movement between production stations and assembly lines. Among them, there are primarily AGVs that move on predetermined routes and autonomous AMRs capable of independent navigation and decision-making in a changing work environment.

Fig. 2. Autonomous Mobile Robot – MIR100 with roller feeder [19]

AGVs are autonomous vehicles that operate on predefined routes marked with markers, magnetic tapes, or static maps, ensuring a high level of predictability and safety. They are primarily used in environments with repetitive material flows, such as production lines or fixed-configuration warehouses. Their design is based on deterministic control models, which keeps the risk of collisions relatively low, although at the cost of limited operational flexibility [9, 32]. Safety and obstacle-avoidance testing requirements emphasize the need for standardized methods for evaluating AGV navigation in industrial settings [20].

AMRs are mobile robots with a high degree of autonomy, using LiDAR, cameras, SLAM algorithms and sensor fusion to self-map the environment and dynamically plan trajectories without physical guiding infrastructure. Because they can adapt to environmental changes, they can safely operate in areas shared with people, making them a more flexible solution than AGVs. The effectiveness of AMR perception depends on combining data from multiple sensors, thereby increasing the system's resistance to interference [1]. In warehouse applications, high docking accuracy is achieved by integrating LiDAR with machine learning algorithms, and testing in a digital twin environment allows for safe validation of robot behavior before deployment [13, 28].

Light Detection and Ranging (LiDAR) systems enable mobile robots to accurately map their surroundings by measuring the return time of laser pulses, allowing them to generate point clouds and accurate maps of space used for navigation, location and obstacle detection. In in-house transport, this technology ensures high measurement stability, resistance to changing lighting conditions, and real-time operation, which significantly increases robot safety. The integration of LiDAR with machine learning algorithms improves the accuracy of docking and object recognition and standardized navigation tests of mobile robots are based on the analysis of LiDAR data as the primary source of perception [3]. In warehouse applications, LiDAR also serves as a space-mapping sensor and as an element of digital twins, supporting the testing of robot working environments [19].

AGVs use navigation systems based on induction loops, QR codes, magnetic or optical lines, while AMRs use advanced LIDAR sensors, 3D cameras, vision systems, and real-time SLAM (Simultaneous Localization and Mapping) algorithms to map location and space in real time. The integration of these technologies enables autonomous robots to analyze their surroundings, detect obstacles, and respond adaptively, allowing them to operate safely alongside humans and in dynamic industrial environments. Modern intralogistics systems are based on a combination of mobile robots and IT platforms from the MES (Manufacturing Execution System), ERP (Enterprise Resource Planning), and WMS (Warehouse Management System) classes, which ensures full synchronization of transport processes with production planning and warehouse management [9].

2.2. Applicable standards and guidelines

However, operating transport robots requires strict technical and organizational safety rules. A key element is to ensure the reliability of the control systems, which are responsible for controlling speed, direction of movement and emergency stop functions. These systems must be designed to ensure resistance to damage and logical errors, as reflected in the safety level (Performance Level) requirements set out in the PN-EN ISO 13849 and PN-EN 62061 standards. An indispensable element of modern designs is also the presence of advanced obstacle detection systems, using various sensor technologies, which enable early detection of objects in the vehicle's path and take preventive actions [10]. Equally important is the introduction of visualization and warning systems that inform workers about the presence and trajectory of robot movement. From an operational safety perspective, the role of the human factor cannot be overlooked – proper operator training, adherence to safety procedures, proper marking of work zones, and effective communication between humans and the automated system are the foundation for maintaining a high level of protection [15].

Table 1. The overview of AGV’s main standards, technical specifications (TS) and guidelines for mobile robot systems

Standard no.	Standard title
2006/42/EG	Machinery directive
EN 1525:1997	Safety of industrial trucks – Driverless trucks and their systems
PN-EN ISO 3691-4:2024-01	Safety requirements and verification methods for driverless industrial trucks and their systems.
ISO/IEC GUIDE 51:2014	Safety aspects – Guidelines for their inclusion in standards
ISO 10218-1:2011	Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots
ISO 10218-2:2011	Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration
ISO 13849-1:2015	Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design
ISO 13849-2:2012	Safety of machinery – Safety-related parts of control systems – Part 2: Validation
DIN EN 614-1:2009	Safety of machinery – Ergonomic design principles – Part 1: Terminology and general principles
VDI 2510-2: 2013	Automated Guided Vehicle Systems (AGVS) – Safety of AGVS
ISO/TS 15066:2016	Robots and robotic devices – Collaborative robots
ANSI/RIA R15:06-2012	Industrial Robots and Robot Systems – Safety Requirements

3. Safety systems used in mobile robots

3.1. Solutions used in industry

Safety systems implemented in mobile robots operating in industrial environments constitute a multi-layered technical and organizational structure, the main goal of which is to minimize the probability of adverse events and limit the effects of possible failures. From a safety engineering perspective, the architecture of these systems should conform to design principles in line with functional safety and risk management standards. In practice, this means that individual safety functions must be designed and implemented with appropriate levels of reliability, redundancy and diagnostic mechanisms in mind, with clearly defined acceptance and testing criteria. The basic building block of security systems is a wide range of perceptual sensors that enable the detection of obstacles, the identification of people and the assessment of dynamic environmental conditions. The most commonly used solutions include LIDAR scanners, stereoscopic and 3D cameras, radars and ultrasonic sensors. Multimodal sensing, combining data from different sources, helps increase immunity to environmental interference and reduce the risk of misdetection. Machine vision technologies and SLAM algorithms simultaneously provide the information necessary for precise vehicle location and planning safe trajectories, which is especially important in environments with high traffic dynamics and variable workspace topologies [24].

Above the sensory layer, there are real-time safety control mechanisms, including functional safety systems that implement logic for responding to detected threats, such as speed limitation, controlled stop or obstacle avoidance. Commercial solutions use separate, certified safety components (e.g. safety PLC, PL/SIL certified controllers) that perform critical functions independently of the main control system, which corresponds to the principle of separation of tasks and reduction of system risk [5, 6]. Ensuring the ability to stop safely requires implementing emergency braking mechanisms and physical restraints, such as vigilant bumpers and crash energy suppression systems, especially in applications where personnel come into direct contact. An important element of the safety architecture is real-time communication and location systems (RTLS) and V2X (Vehicle-to-Everything) solutions, which enable the exchange of information about the robot's position, status and intended trajectories between robots, infrastructure and operators. These systems promote traffic predictability and the coordination of multiple units in the plant space, reducing the risk of collisions and operational overload. At the same time, however, their implementation imposes the obligation to secure transmissions against interference and cyber-attacks; the integration of cryptographic mechanisms and access policies is indispensable [22]. In response to the growing importance of cybersecurity, practices such as segmentation of industrial networks, monitoring for communication anomalies, and software updates in secure mode are also being developed.

3.2. Human-robot collaboration

Sharing a workspace between humans and mobile robots requires the use of Human-Robot Collaboration (HRC) principles, which determine acceptable forms of interaction and safety parameters based on the distance and speed of approach. Such solutions allow you to maintain a balance between the efficiency of logistics processes and the protection of employees' health and lives. Human-Robot Collaboration (HRC) enforces specific solutions embedded in the safety layer. Designing space-sharing zones, defining safe approach speeds, using projection and signaling systems, and introducing the so-called "soft-fencing" borders make it possible to maintain an ergonomic and predictable working environment while ensuring personnel safety [11]. Projection solutions that visually communicate the robot's planned trajectory or intentions serve as a social interface between the machine and humans, reducing uncertainty and supporting appropriate employee behavior in a shared space [31]. An important component of safety systems is the predictive diagnostics and condition-monitoring layer, which integrates operational data with predictive models to detect deviations from nominal parameters early. These practices reduce the likelihood of failures due to mechanical component wear or sensor degradation and enable maintenance planning that minimizes the impact on the continuity of production processes [22]. Modern deployments increasingly use digital twins to simulate contingency scenarios and test mitigation strategies in virtual environments before applying them in the real world. At the interface between technology and organization lies the implementation of procedures for verification and validation of security systems. These processes include acceptance tests, simulation scenarios, compliance audits, and methodological tests. A comprehensive approach to safety requires not only the use of integrated technologies but also the formalization of operational policies, staff training and incident response procedures, which are prerequisites for sustained safety in the operation of mobile robots [33].

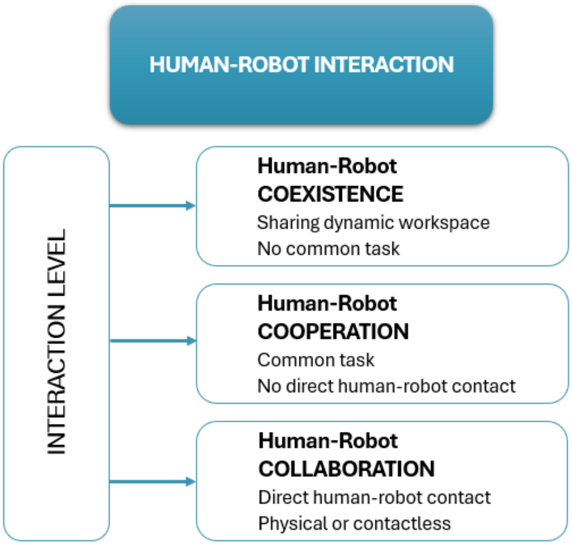

Fig. 3. Human-robot interaction types on the basis of interaction level [12]

The use of mobile robots brings measurable benefits by reducing the number of accidents resulting from human error, but it also raises new challenges in risk assessment, monitoring technical condition and maintaining the cybersecurity of systems. Therefore, the correct implementation of PN-EN ISO 3691-4 and related safety standards forms the basis for the sustainable development of modern transport systems in industrial companies that strive to achieve a high level of automation while ensuring full protection of users and the working environment.

3.3. Safety aspects of mobile robots in the internal transport

The safety of mobile robot operation in the company environment is multidimensional and includes both traditional mechanical and control issues as well as modern challenges related to perception, sensor fusion, cybersecurity and integration with enterprise resource management systems. In the area of internal transport, where robots move in a limited and often shared space, the requirements for reliability, predictability of behaviour and emergency responses are particularly restrictive. Key aspects of security can be considered from the perspective of four interdependent layers: perceptual, decision-making and controlling, communication (including cybersecurity), and organizational and environmental.

The perceptual layer provides the basis for safety – it is the quality of obstacle detection, the recognition of people and objects, and the stability of the sensory signal that determine the correctness of subsequent control decisions. A review of the issue of sensor fusion indicates that individual sensors (e.g. 2D LiDAR, camera) have limitations under certain conditions (e.g. light reflections, dust, variable lighting) and that the use of multimodal solutions significantly increases the system's resistance to detection errors. A practical solution for the task of precise docking and rack detection using 2D LiDAR and machine learning algorithms, which significantly reduces location errors during loading and unloading operations. As docking operations are critical to personnel and cargo safety, it is important that detection algorithms are both fast and stable in industrial environments. At the same time, the implemented approaches must include mechanisms to assess classification confidence, enabling transfer of control to safe, deterministic contingency procedures in low-confidence situations.

The decision-making and control layer includes trajectory-planning algorithms, obstacle-avoidance mechanisms, and formation control for multi-robot fleets. A standard test method for assessing the navigation and obstacle avoidance capabilities of AGVs and AMRs operating under real plant conditions and provides a tool to verify that the robot's behavior meets safety expectations. In environments where multiple units operate simultaneously, planning movement in formations and coordinating reversing and tight maneuvers are critical. Work on movement control in formations shows that precise planning and synchronization of control minimize the risk of collision during simultaneous maneuvers [25]. It is also important to use formal trajectory verification methods (e.g. provably safe proofing), which allow one to mathematically confirm the absence of collisions under given environmental assumptions, which is especially important in spaces shared with people [12].

The communication layer and the security of IT systems are elements whose neglect can lead to catastrophic physical consequences. An analysis of security and IT security interactions reveals the interdependencies between cybersecurity vulnerabilities and breaches of the robot's movement layer [26]. For this reason, the design of AGV/AMR systems must take into account the protection of communication channels, device authentication and monitoring of anomalies in network traffic. Integration with IoT platforms and ERP/MES systems, while providing great benefits in asset management and predictive diagnostics, also increases the attack surface and requires software update policies and penetration testing throughout the system lifecycle [28].

The environmental and energy-ecological aspect, although seemingly far from the directly understood safety, has significant operational and health implications. Research on vehicle emissions and fuel consumption in real-world driving, and work on optimizing transport and energy resources within the company, emphasize the need to account for energy consumption and emissions in fleet planning [2, 30]. In practice, long-term power outages, suboptimal battery charging management or poor operating conditions can lead to emergency situations, further complicating safety issues. In addition, green logistics work and energy consumption simulations provide tools to help minimize carbon footprint and plan fleet work cycles safely and sustainably [7, 10].

Organizational and implementation aspects are an indispensable component of the security system. Implementing AMRs in high-bay warehouses requires specific design and procedural solutions [19]. Designing AMRs for high-bay racks requires adapting the warehouse infrastructure and training staff. At the same time, acceptance tests and simulations in the digital twin of the operational environment enable the evaluation of contingency scenarios without risk to the actual installation and serve as a tool to optimize security procedures before deployment [28].

The integration of all of the above layers requires a systemic approach that aims to reduce the remaining risk to an acceptable level, while accounting for cost and utility. In practice, this means combining sensory redundancy with formal trajectory verification methods, IT security, energy management, and staff training programs. In light of literature analyses, the critical areas of further research and implementation remain: standardization of tests for the assessment of navigation capabilities and obstacle avoidance, the development of interference-resistant methods of sensor fusion [1, 20], and methods for validation of machine learning algorithms used in perception and docking [13]. The growing role of digital twins and multi-agent simulations enables advanced operational testing that was previously too expensive or risky to conduct in a production environment.

4. Risk analysis in the operation of transport robots

4.1. Risk assessment and verification process

Risk analysis in the context of the operation of transport robots should be understood as a systematic, iterative process of identifying hazards, assessing their probability and consequences, and designing and implementing risk reduction measures to achieve an acceptable level of risk in accordance with applicable safety standards and rules. In practice, this process is carried out in accordance with an ISO 12100-based approach, which imposes the obligation to eliminate risks at the design stage and then reduce the remaining risk through technical measures, administrative safeguards and user instructions. The analysis methodology includes both qualitative hazard identification techniques and quantitative risk assessment methods, such as FMEA, HAZOP and LOPA, which enable the estimation of the probability of adverse events and their potential impacts. The basic categories of hazards associated with transport robots include the risk of collision with people and objects, the risk of crushing or impact caused by the weight and speed of the vehicle, control system failures leading to uncontrolled behavior, software errors affecting location and trajectory planning, loss of communication with superior systems, sensor malfunction under interfering conditions, and threats resulting from cyberattacks on systems communication [24]. Environmental factors such as variable pavement properties, lighting conditions affecting vision systems, and problems related to interaction with third-party transport systems are additional risk factors, underscoring the importance of interoperability testing and communication standardization [16].

The risk assessment process requires precise identification of contingency scenarios and analysis of their courses of action under realistic conditions. Formal methods and verification techniques, such as provably safe motion planning proposed in the literature, allow for mathematical proof of trajectory safety in the presence of dynamic obstacles and sensory uncertainty, which is particularly important in applications shared with personnel [18]. At the same time, it is necessary to take into account organizational aspects: analysis of operator competences, emergency procedures, ergonomic arrangement of work zones, and the impact of automation on work structure and possible dehumanization phenomena that may indirectly affect safety and incident-reporting culture [29]. In practice, risk reduction is based on the synergy of technical and organizational measures. Technical measures include implementing obstacle detection and classification systems, redundancy for critical sensors and control systems, collision-energization limitation mechanisms, RTLS systems and speed control. Organizational measures include implementing health and safety procedures, providing training, zoning workspaces and conducting safety audits. A key element is also the change management system, which requires a re-analysis of risk with each modification to the software, fleet configuration or infrastructure layout [5].

4.2. Safety indicators and communication challenges

Effective risk management also requires implementing mechanisms to monitor safety performance indicators (KPIs), such as the number of near-accident events, incident response time, availability of safety features, and the number of diagnostic readings outside the limit. This data provides the basis for trend analysis and continuous improvement. Integration and scenario tests are also needed, including those proposed in the literature to assess robots' ability to detect and avoid obstacles in industrial settings [24]. In light of the above, risk analysis in the operation of transport robots should not be understood as a one-off formal document, but as a cyclical process, integrated into the company's safety management system, combining technical verification of systems, analysis of human behavior, cyber threat assessment, and audit and improvement procedures. Such a comprehensive perspective allows not only to minimize immediate threats, but also to build the organization's resilience to new challenges that arise as autonomous technologies develop.

The development and implementation of a prototype transport robot in an industrial environment illustrates the process from the conceptual phase to integration into the plant infrastructure. Prototype research indicates that key design decisions include the choice of navigation strategies, sensory architecture, and safety mechanisms in contact with the working environment. The authors involved in the development of prototypes emphasize the need to use a LIDAR sensor for effective mapping of space and 3D cameras for object classification, enabling simultaneous vehicle location and obstacle identification [24, 29]. In design practice, prototypes demonstrate that integrating perceptual systems with independent safety logic (separate systems that respond to detected hazards) is necessary to achieve the safe stop function and reduce the impact energy in collision situations. The experience gained during prototype work also confirms that early implementation of predictive diagnostics and interoperability testing mechanisms minimizes the risk of subsequent modifications in production conditions, and simulations and tests on digital twins shorten the solution validation cycle [27]. The most important challenge remains ensuring sensor consistency across different environmental conditions, which requires the use of multimodal sensor sets and calibration procedures.

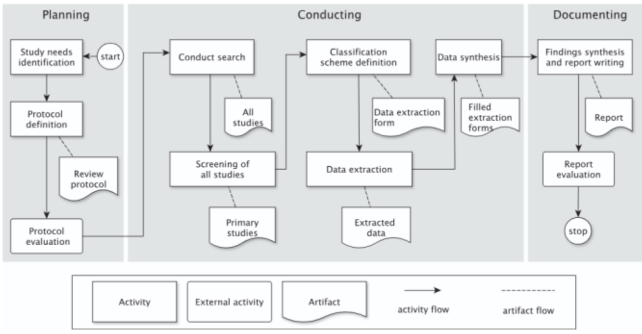

Fig. 4. Overview of the whole mapping process [6]

4.3. Case study and implementation

Implementations of AGV/AMR systems in commercial intralogistics illustrate the scale and consequences of integrating mobile automation with warehouse and production management systems [4]. Review and analytical literature indicate that these implementations generate significant efficiency benefits but, at the same time, put the organization's communication architecture and security procedures to the test [17]. In warehouse and distribution center contexts, it is reasonable to use central traffic orchestration systems that coordinate the trajectories of multiple units and minimize conflicts through task prioritization and dynamic route planning; Such solutions reduce the occurrence of blockages and reduce the risk of collisions, but they require the implementation of communication security and critical information redundancy mechanisms [32]. The literature also describes practical aspects of organizational security that accompany implementations: proper zoning of space, personnel training and service procedures, which together form a layer of risk reduction complementary to technical solutions [14, 32]. The operational challenge in large deployments is to ensure interoperability between components from different vendors and maintain fleet continuity in just-in-time and just-in-sequence scenarios, which requires a rigorous change management policy and predictive maintenance schedules.

Projects focused on perceptual safety, obstacle detection testing and IoT integration show how advanced validation methods and data architectures contribute to increased safety in the operation of mobile robots. Research on vision systems and detection algorithms shows that using a single type of sensor is insufficient; it is necessary to combine LIDAR, stereoscopic cameras and ultrasonic sensors to achieve immunity to interference and lighting conditions [24]. The literature on testing obstacle detection and avoidance methods highlights the importance of developing standardized test scenarios that allow robots to assess their ability to move safely in the presence of human movement and irregular objects [21]. Implementations integrating IoT solutions focus on the collection and analysis of diagnostic data in real time, enabling predictive mechanisms and rapid operational responses to deviations from the nominal operating state. At the same time, this integration requires special attention in terms of communication security and data access policies [23]. Among the important practical conclusions, experts point to the need to conduct continuous audits of perception systems and tests of tolerance to software errors, which, in many cases, are the main sources of unforeseen behavior.

A comparative analysis of all three studies confirms that the successful implementation of mobile robots requires the parallel shaping of three areas: the technical and engineering layer, including sensor redundancy and certified safety systems, the IT layer ensuring communication integrity and predictive diagnostic mechanisms and the organizational layer managing training, service procedures and integration tests. The literature indicates the need to design security from the outset of system development and to conduct an iterative risk analysis with each solution modification [6, 15]. The final conclusion from the analyzed cases is that the safety of mobile robot operation is a continuous, multidimensional process, the success of which depends on the skillful combination of perceptual technologies, control architectures, data management practices and the company's organizational culture.

5. Development directions and innovations in the field of the safety of mobile robots

5.1. Development concepts and trends

The directions of development of safety technologies for mobile robots are evolving in response to parallel advances in sensors, artificial intelligence, communication systems and engineering methods related to functional safety. From an engineering perspective, the "safety by design" approach is becoming increasingly important, which assumes the introduction of safety measures at the conceptual and design stages of the system, rather than adding protective functions during the operational phase. Such a strategy implies a close integration of the requirements compliant with PN-EN ISO 3691-4:2024-01 and the principles of risk assessment and mitigation described in ISO 12100 with advanced engineering practices for redundancy, separation of functions and predictive diagnostics (PN-EN ISO 3691-4:2024-01; ISO 12100). The implementation of "safety by design" means, among other things, the use of control architectures with a clear separation of critical safety functions in separate, certified modules, the implementation of formal validation processes and the conduct of iterative risk analyses with each change in the configuration of the fleet or operating environment [6, 32]. Advances in sensor perception and fusion are the second major innovation trend for improving safety. Multimodal perception fusion systems combine data from LIDARs, stereoscopic cameras, ultrasonic sensors, and radar to increase the system's resistance to interference conditions, varying lighting, and irregular obstacles. Research on vision systems and their integration indicates that sensory redundancy and adaptive algorithms for combining information are key to minimizing classification errors and decision delays, which, in the context of mobile robots, translate directly into reduced collision risk [11, 21]. In parallel, SLAM algorithms and probabilistic environmental recognition techniques enable more consistent trajectory planning and safe movement in a variable topology environment, and their combination with anomaly detection mechanisms allows for early detection of sensor degradation and triggering emergency procedures [22].

Another trend is the implementation of formal and verification methods that enable proving the correctness of motion algorithms and trajectory planning under uncertainty. The concepts of "provably safe motion planning" and the use of formal methods for the analysis of control software are gaining importance as industrial robots increasingly operate in shared spaces with humans. These methods allow mathematical verification that, under the given environmental assumptions, the algorithms' trajectories and decisions meet certain safety conditions, which is particularly important in scenarios where traditional scenario tests do not provide a full guarantee of immunity to rare but critical events [18, 21]. From a software engineering perspective, the development of tools for automated testing, simulation on digital twins and continuous integration of security testing simplifies the validation process, shortens deployment cycles and increases the functional confidence of systems [27].

The next direction of development focuses on integrating artificial intelligence with security requirements, including issues related to the interpretability and predictability of learning system behavior. Machine learning applications for obstacle detection, object classification and adaptive planning offer better environmental adaptation but also introduce new risks, including the difficulty of validating models and the potential for unforeseen behavioral errors. In response to these challenges, explainable AI (XAI) techniques, predictive confidence-monitoring mechanisms, and hybrid architectures that combine traditional security rules with learning components are being developed to ensure critical decisions always have a backup, deterministic execution path [23].

5.2. Organizational and social aspects

Organizational and social aspects cannot be overlooked, which are an integral part of future security. Directions of development include the development of training standards, certification procedures and uniform security metrics that will enable comparable risk assessment between implementations [5]. At the same time, the importance of research on the ergonomics of human-robot interaction, the design of intuitive interfaces communicating the robot's intentions (e.g. projections, light signals), and the monitoring of the impact of automation on work structure and dehumanization aspects, which affects social acceptance and safety culture in the organization, is growing in importance [29, 31]. In practice, these innovations manifest in dynamic space-sharing procedures that allow for flexible adaptation of speeds and safety zones to the current operational context. The development of standardization and testing methods is essential to turn technological innovations into virtually safe solutions. Proposals to create standardized test scenarios, perception benchmarks and standardized security KPIs will increase transparency and comparability of the security properties of individual systems. The tests proposed in the literature on obstacle detection and avoidance, as well as formal assessment methods, should be complemented by dynamic integration tests involving humans in realistic operating conditions, which will ensure that systems are better prepared for real-world operations [21]. The future of mobile robot safety lies in the holistic combination of safety by design, advanced sensor perception and fusion, formal verification of algorithms, responsible use of artificial intelligence, cyber resilience, and developed organizational practices and testing standards. Only the integration of these development directions, implemented at both the technology and management levels, will enable the safe and scalable deployment of autonomous transport systems in complex industrial environments [6].

6. Summary and conclusions

The development of automation of internal transport and the popularization of mobile robots AGV and AMR are key elements of the transformation of intralogistics in manufacturing and warehouse companies [20]. The analysis of the literature clearly indicates that the implementation of such systems brings significant operational benefits: increased efficiency of material flow, reduced employee workload and the possibility of flexible adaptation of processes to changing demand [22, 32]. However, achieving these benefits requires the consistent application of security design principles, iterative risk analysis, and the implementation of multi-layered protection systems operating at the design, technical, and organizational levels [5, 8].

Standards, in particular PN-EN ISO 3691-4, ISO 12100 and ISO 13849, form the basis for defining safety requirements for mobile robots – from the detection of people to the reliability of control systems, to requirements for emergency braking and separation of work zones [8, 21]. Their integration enables the implementation of a "safety by design" approach, in which eliminating hazards at the source and using certified, redundant components form the foundation of a reliable system architecture [6, 12]. In this context, critical safety functions must be implemented by independent elements and adaptive algorithms supported by deterministic back-up mechanisms [18, 19].

The technical safety of mobile robots is based on multimodal environmental perception and control architectures capable of maintaining safe operating modes. The fusion of data from LIDARs, stereoscopic cameras, radars and ultrasonic sensors increases the resilience of systems to interference and changing environmental conditions, reducing the number of false detections and the risk of misclassification of objects [16]. Parallel developed SLAM algorithms and methods of formal trajectory verification enable safe movement in a shared environment with humans, provided that they are accompanied by an analysis of behavior in borderline situations [12, 24]. Predictive diagnostics and the use of digital twins to simulate emergency scenarios are playing an increasingly important role, improving the system's ability to detect degradation early and plan maintenance.

Organizational aspects remain integral to the safety of mobile robots. These include staff training, appropriate zone signage, development of service procedures, adherence to change management principles, and ensuring proper human-robot communication [30]. With the increasing integration of AMRs with IT infrastructure and IoT systems, the importance of cybersecurity, data access policies and transparency of the operation of autonomous systems towards employees is growing [26].

The future of mobile robot safety is based on the development of standardized tests, integration scenarios involving humans, and perception benchmarks that will enable comparable evaluation of systems from different manufacturers [20, 21]. Further advances in sensory fusion, formal methods, predictive diagnostics, artificial intelligence and cyber resilience will lead to increased reliability and scalability of deployments [1, 12]. The safe operation of mobile robots remains a continuous process, requiring simultaneous improvement of technology, organizational procedures and safety culture in enterprises [8, 16].

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