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Development of autonomous mobile robots for industrial automation: a review of control systems, navigation, and obstacle avoidance

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ABSTRACT

Autonomous mobile robots (AMRs) are increasingly important in industrial automation because they can transport materials, support production operations, and perform repetitive tasks with limited human intervention. Their effective deployment depends on the integration of motion control, localization, navigation, and obstacle avoidance within a reliable robotic architecture. However, industrial environments introduce substantial challenges, including changing layouts, moving workers, dynamic obstacles, localization errors, and strict operational safety requirements. This review examines the development of autonomous mobile robots up to 2015, focusing on control systems, navigation approaches, and obstacle-avoidance techniques, while identifying their capabilities and limitations in industrial applications.

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1. INTRODUCTION

Industrial automation has traditionally relied on fixed production lines, conveyor systems, and automated guided vehicles (AGVs) to support material handling and manufacturing operations. Although these technologies improve productivity, conventional AGVs commonly depend on predefined routes, magnetic tracks, wires, or other infrastructure-based guidance systems. Such arrangements can become restrictive when production layouts change or when several vehicles must operate in shared spaces. Autonomous mobile robots offer a more flexible alternative because they can perceive their surroundings, estimate their positions, and modify their movements according to environmental conditions [1].

The development of autonomous mobile robots is driven by the need for flexible transportation, efficient material distribution, and adaptable manufacturing processes. Unlike conventional guided vehicles, autonomous platforms can combine onboard sensors, localization algorithms, motion controllers, and planning systems to navigate with reduced dependence on fixed infrastructure. Nevertheless, autonomy does not automatically guarantee reliable industrial operation because the robot must maintain accurate localization and safe motion while responding to unexpected events. The central research problem is therefore how to integrate control, navigation, and obstacle avoidance into a dependable system that can operate in changing industrial environments.

This review addresses that problem by examining three interconnected technological components: control systems, autonomous navigation, and obstacle avoidance. The discussion emphasizes the relationship between these components rather than treating them as isolated technologies. It also considers the practical requirements of industrial deployment, including reliability, computational efficiency, operational safety, and adaptability. The review is limited to research and technical publications available up to 2015, ensuring that no reference published after the specified year is included.

2. ARCHITECTURE OF AUTONOMOUS MOBILE ROBOTS

An autonomous mobile robot generally consists of a mechanical platform, drive system, onboard sensors, processing unit, communication interface, and control software. The mechanical platform determines the robot's mobility and payload capability, while the drive system converts control commands into physical movement. Sensors provide information about the robot's surroundings and internal motion, allowing the processing unit to estimate its state and make navigation decisions. These components must operate together because weaknesses in sensing, computation, or actuation can directly affect overall navigation performance.

The architecture can be organized into perception, localization, planning, and motion-control functions. The perception layer collects information from sensors such as laser scanners, ultrasonic devices, cameras, and wheel encoders. Localization estimates the robot's position and orientation, while planning determines a suitable route toward its destination. The motion-control layer then translates the planned movement into commands for the motors and steering mechanism. Shneier and Bostelman [1] emphasize that manufacturing applications require consideration not only of navigation capability but also of vehicle selection, localization, control, and safe operation around people.

Two broad architectural approaches are commonly relevant to industrial mobile robots. A centralized architecture coordinates navigation and task allocation through a supervisory computer, which can simplify fleet management and global traffic coordination. A decentralized architecture gives individual robots greater responsibility for perception, planning, and local decision-making, potentially improving flexibility when communication is interrupted. In practice, a hybrid architecture can combine centralized production scheduling with onboard navigation and immediate collision-avoidance functions. This arrangement provides a useful balance between system-wide coordination and the ability of individual robots to respond to local conditions.

3. CONTROL SYSTEMS FOR AUTONOMOUS MOBILE ROBOTS

The control system determines how accurately and reliably a mobile robot follows its intended movement. At the lowest level, motor controllers regulate wheel speed, torque, or steering commands according to the robot's mechanical configuration. At a higher level, motion controllers regulate linear and angular movement so that the vehicle follows a desired trajectory. The overall performance depends on the interaction between these control levels, the accuracy of the robot model, and the quality of feedback from onboard sensors.

Feedback control is essential because actual robot movement rarely matches commanded movement perfectly. Wheel slippage, uneven floors, payload variation, mechanical backlash, and external disturbances can produce deviations from the desired trajectory. Closed-loop control addresses these deviations by comparing measured motion with the reference command and adjusting actuator outputs accordingly. Proportional-integral-derivative (PID) control is a practical option for lower-level motor regulation because it is relatively simple to implement and can provide satisfactory performance when the system is properly tuned.

More advanced control approaches can be used when the robot must follow complex trajectories or operate under changing dynamic conditions. Model-based control uses a representation of the robot's motion to predict how control commands affect its future position and orientation. Such approaches can improve trajectory tracking, but their performance depends on the accuracy of the model and the availability of sufficient computational resources. Consequently, industrial designers must balance control precision against implementation complexity, processing requirements, and maintainability.

Control cannot be considered independently of navigation and safety. A navigation system may generate a collision-free path, but poor trajectory tracking can still cause the robot to deviate into an unsafe region. Similarly, a reactive obstacle-avoidance algorithm may identify a safe direction, but the motion controller must be able to execute the required change within the robot's physical acceleration and braking limits. The Dynamic Window Approach developed by Fox *et al.* [2] illustrates this relationship by evaluating feasible velocity commands according to the robot's motion dynamics and its ability to stop safely.

4. NAVIGATION AND LOCALIZATION TECHNIQUES

Autonomous navigation requires a robot to determine its position, understand its environment, select a route, and continuously adjust its movement toward a target. Localization is particularly important because navigation decisions become unreliable when the robot's estimated position differs significantly from its actual position. Industrial environments may contain repetitive structures, similar-looking corridors, reflective surfaces, and changing objects that complicate position estimation. Therefore, robust navigation generally requires a combination of sensor measurements, environmental representations, and localization algorithms.

Odometry is one of the simplest localization techniques because it estimates movement from wheel rotation or other motion measurements. Its principal advantage is that it can operate continuously without requiring a detailed external map or infrastructure. However, small measurement errors accumulate over time, producing position drift that can become significant during long operating periods. For this reason, odometry is often combined with external sensing or map-based localization to reduce accumulated uncertainty.

Simultaneous localization and mapping (SLAM) provides a more comprehensive approach when a robot must estimate its position while constructing or updating a map. Durrant-Whyte and Bailey [3], [4] describe SLAM as a fundamental problem in mobile robotics, involving the estimation of both robot motion and environmental structure. SLAM can support operation in unfamiliar environments, but its performance depends on sensor quality, computational resources, and the ability to recognize previously observed features. In industrial facilities, the presence of moving equipment and changing storage arrangements can further complicate map consistency and localization.

Different sensors provide complementary information for navigation. Laser range finders can produce accurate distance measurements and are useful for detecting nearby structures, while ultrasonic sensors offer a relatively simple means of measuring distances to obstacles. Cameras can provide visual information about environmental features, but their performance may be affected by lighting conditions, motion blur, and visual ambiguity. Combining multiple sensor sources can improve robustness, provided that the system can manage measurement uncertainty and differences in sensor update rates.

Global path planning and local navigation perform different but complementary functions. Global planning determines a route from the starting position to the destination using a map or environmental representation. Local navigation adjusts the robot's movement in response to nearby obstacles, unexpected changes, and deviations from the planned route. Khaksar *et al.* [5] review approaches to motion path planning in unknown environments and discuss methods such as graph-based search, sampling-based planning, and heuristic techniques. For industrial applications, the choice of method should consider route quality, computational cost, environmental uncertainty, and the frequency of layout changes.

5. OBSTACLE-AVOIDANCE TECHNIQUES

Obstacle avoidance is a critical requirement for autonomous mobile robots operating in factories, warehouses, and other shared industrial spaces. Obstacles may include stationary objects such as shelves, pallets, and machinery, as well as moving objects such as workers, forklifts, and other mobile robots. A robot must detect these objects, estimate their relative positions, and select a movement that avoids collision without unnecessarily interrupting its task. Effective obstacle avoidance therefore requires both reliable sensing and a control strategy capable of responding within an appropriate time.

The vector field histogram (VFH) is an established approach to real-time obstacle avoidance. Borenstein and Koren [6] introduced a method that uses a histogram-based representation of obstacle density to identify suitable steering directions. The approach processes range measurements and selects a direction that reduces collision risk while maintaining progress toward the target. Its practical advantage is the ability to support smooth movement through cluttered environments, although its effectiveness depends on sensor coverage, parameter selection, and the quality of the environmental representation.

The dynamic window approach (DWA) provides another influential method for local obstacle avoidance. Rather than selecting a direction solely from geometric information, DWA evaluates candidate translational and rotational velocities that are physically reachable within a short time interval. It then considers whether the resulting trajectories allow the robot to stop safely before reaching an obstacle. This makes the approach particularly relevant to mobile platforms whose acceleration, braking, and turning capabilities must be considered during navigation [2].

Potential-field methods offer a different approach by representing the target as an attractive influence and obstacles as repulsive influences. The robot moves according to the resulting direction of motion, which can provide a computationally straightforward way to react to nearby objects. However, these methods can encounter local minima, where the robot becomes trapped in a position from which the combined influences do not produce useful progress. Such limitations demonstrate why obstacle avoidance should be integrated with global planning rather than treated as a complete navigation solution.

The main characteristics of selected navigation and obstacle-avoidance techniques are summarized in Table 1. The comparison highlights that no single method provides an ideal solution for every industrial environment. Map-based approaches can support systematic route planning, while reactive methods are useful for responding to immediate changes. Sensor fusion and SLAM can improve environmental awareness, but they introduce additional computational and implementation requirements.

Table 1. Comparison of selected navigation and obstacle-avoidance techniques

Technique	Main function	Advantages	Main limitations
Odometry	Motion and position estimation	Simple, continuous, low infrastructure requirement	Accumulated drift and wheel-slip errors
SLAM	Simultaneous mapping and localization	Supports navigation in previously unknown environments	Computational complexity and sensitivity to environmental changes
Graph-based planning	Global route generation	Structured route search and map-based planning	Requires a suitable map and may need replanning
Vector field histogram	Local obstacle avoidance	Reactive steering and real-time obstacle handling	Depends on sensor quality and parameter selection
Dynamic window approach	Velocity-based local planning	Considers motion constraints and stopping capability	Performance depends on dynamic modeling and computation

Table 1 shows that the methods differ in their operational roles and should not be regarded as direct substitutes. Odometry and SLAM primarily support localization, whereas graph-based planning determines a global route. VFH, DWA, and potential-field methods are more directly concerned with local motion decisions and obstacle avoidance. A practical industrial robot can therefore combine these techniques, using localization and global planning to establish its route while applying reactive control to handle nearby obstacles.

6. INDUSTRIAL APPLICATIONS AND IMPLEMENTATION CHALLENGES

Autonomous mobile robots can support several industrial activities, particularly material transportation, warehouse logistics, work-in-process delivery, and movement of components between production stations. Their flexibility can reduce dependence on fixed conveyor arrangements and allow material flows to be adjusted when production requirements change. In warehouses, mobile robots can transport goods between storage and dispatch areas, potentially reducing repetitive manual handling. Their effectiveness, however, depends on the integration of navigation with production scheduling, traffic management, and the facility's operational procedures.

The transition from laboratory prototypes to industrial deployment introduces challenges beyond algorithm performance. Robots must operate reliably over extended periods, tolerate changing payloads, and maintain predictable behavior in environments shared with human workers. Communication failures, sensor degradation, unexpected obstacles, and changes in floor conditions can interrupt autonomous operation. Shneier and Bostelman [1] emphasize the importance of safety considerations in manufacturing applications, particularly when mobile robots operate in collaborative environments.

Multi-robot coordination is another important implementation issue. When several vehicles share narrow passages, loading areas, or intersections, independent navigation decisions can create congestion or deadlock. A fleet-management system can assign tasks, coordinate routes, and regulate traffic to improve overall throughput. However, centralized coordination must be designed to avoid becoming a single point of failure, and individual robots still require local capabilities to respond safely when immediate conditions differ from the global plan.

A further challenge is the trade-off between autonomy and operational predictability. Highly flexible navigation can accommodate changing layouts, but it may also produce routes that are difficult for operators to anticipate or validate. Conversely, highly structured routes can simplify safety assessment but reduce adaptability when the production environment changes. Industrial implementation should therefore select the appropriate autonomy level according to task requirements, environmental complexity, safety expectations, and the cost of operational interruptions.

7. RESEARCH GAPS AND FUTURE DEVELOPMENT

The literature available up to 2015 demonstrates substantial progress in localization, mapping, motion control, and reactive obstacle avoidance. Nevertheless, many techniques are developed and evaluated as individual components rather than as fully integrated industrial systems. A localization algorithm may perform well in a controlled environment but become less reliable when the environment contains repetitive structures or moving objects. Similarly, an obstacle-avoidance method may prevent collisions but fail to maintain efficient task execution when traffic becomes dense.

One important research direction is the development of integrated architectures that combine global planning, local obstacle avoidance, and feedback control. Such architectures should consider not only

whether a path is collision-free but also whether the robot can follow it safely under realistic mechanical and environmental constraints. Another direction concerns robust sensor fusion, particularly when individual sensors are affected by dust, lighting variation, reflective surfaces, or temporary occlusion. These developments should be evaluated using realistic industrial scenarios rather than relying exclusively on simplified laboratory demonstrations.

Safety and human-robot interaction also require continued attention. Industrial robots must recognize that workers and other vehicles may move unpredictably, and they should adapt their speed and trajectories accordingly. Reliable emergency stopping, predictable behavior, and appropriate supervisory control are essential for deployment in shared workspaces. These requirements indicate that future development should treat safety, navigation, and productivity as interconnected design objectives rather than separate considerations.

8. CONCLUSION

Autonomous mobile robots provide an important technological foundation for more flexible industrial automation. Their performance depends on the coordinated operation of mechanical platforms, sensing systems, localization algorithms, navigation planners, and motion controllers. Feedback control supports accurate movement, while odometry and SLAM provide position estimation and environmental mapping. Global planning, VFH, DWA, and other reactive methods contribute complementary capabilities for route generation and obstacle avoidance.

The review indicates that reliable industrial autonomy cannot be achieved through a single algorithm or subsystem. Instead, practical systems require an integrated architecture that combines accurate localization, efficient route planning, dynamic obstacle detection, and motion control consistent with the robot's physical limitations. Industrial deployment must also account for fleet coordination, human safety, communication reliability, and changing production requirements. Continued progress in these areas can strengthen the role of autonomous mobile robots as adaptable and dependable components of industrial automation.

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