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LOCOMOTION MECHANISMS FOR MOBILE ROBOTS: CLASSIFICATION, KINEMATIC-DYNAMIC MODELING, AND MOTION CONTROL – A REVIEW

BY

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Abstract. The paper presents a comprehensive analysis of mobility and locomotion mechanisms for mobile robots, emphasizing their role in dynamic, human-shared environments. It explores the evolution from traditional Automated Guided Vehicles to autonomous platforms capable of safe interaction with humans, highlighting the importance of mobility as a multidisciplinary concept integrating mechanical design, control, and safety compliance. A detailed classification of locomotion systems is provided, including differential drive, Ackermann steering, omnidirectional wheels, tracked platforms, legged robots, and hybrid configurations, with a focus on their advantages, limitations, and application domains. Furthermore, the study addresses kinematic and dynamic modeling principles essential for accurate motion prediction and control, followed by an overview of advanced motion control strategies such as nonlinear controllers, model predictive control, and learning-based approaches. Performance criteria related to maneuverability, energy efficiency, stability, and compliance with international safety standards are discussed.

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1. Introduction

The rapid development of mobile robotic systems over the last two decades has led to a significant transition from classical Automated Guided Vehicles (AGVs) toward autonomous mobile robots capable of operating in dynamic, partially unstructured environments in the presence of humans. These systems are commonly referred to in the scientific literature as mobile robots and represent a key technological pillar of the industry 4.0 paradigm (Siegwart *et al.*, 2011; Villani *et al.*, 2018).

Mobile robots are defined as mobile robotic systems specifically designed to safely operate in shared workspaces with human operators, without the need for physical safety barriers. They are required to perceive their environment, make autonomous decisions, and interact with humans in a predictable and safe manner (ISO, 2016). Unlike traditional industrial robots, which are confined to isolated work cells, mobile robots are directly integrated into real operational workflows, thus imposing additional constraints related to safety, ergonomics, adaptability, and interaction transparency.

One of the most critical subsystems of any mobile robot is the mobility system, as it directly determines both the robot's ability to navigate within crowded environments and the overall level of safety in human–robot interaction. Mobility is not merely a mechanical feature, but rather a multidisciplinary concept that integrates mechanical design, motion control, environment perception, and compliance with functional safety standards (Siciliano and Khatib, 2016). The selection of a locomotion mechanism has a direct impact on platform stability, maneuverability, energy efficiency, acoustic noise, mechanical wear, and behavior during accidental contact scenarios.

Mobile robots are increasingly deployed in a wide range of application domains, including internal logistics in factories and warehouses, where they transport materials and components; healthcare environments, where they support the distribution of medicines, medical instruments, and supplies; and retail spaces, where they assist with replenishment, inventory monitoring, and customer support services (Ivanov *et al.*, 2019; Sharma *et al.*, 2023). In all these domains, continuous co-presence with humans imposes strict limitations on motion speed, braking capability, impact forces, and overall dynamic behavior.

From a regulatory perspective, the safety of robots is explicitly addressed by dedicated international standards, such as ISO/TS 15066 for human–robot collaboration and ISO 3691-4 for driverless industrial trucks and their systems. These standards define limits for maximum allowable speed, kinetic energy, stopping distances, detection zones, and redundancy requirements for safety-

related subsystems (ISO, 2016; ISO, 2023). Within this framework, the locomotion mechanism cannot be selected solely based on kinematic or energetic performance but must also satisfy strict certification and compliance constraints specific to collaborative operation.

The scientific literature clearly shows that there is no universally optimal mobility solution for mobile robots. Different locomotion mechanisms, such as differential drive, Ackermann steering, omnidirectional platforms, tracked systems, and even legged structures exhibit distinct advantages and limitations depending on the application, surface characteristics, level of human interaction, and payload requirements (Campion *et al.*, 1996; Dudek and Jenkin, 2010). This diversity necessitates a rigorous, comparative analysis grounded in both theoretical modeling and experimental evidence.

The objective of this paper is to provide a comprehensive and structured analysis of mobility in mobile robots, with a specific focus on locomotion mechanisms, motion modeling, performance criteria, and safety implications. The paper aims to provide a coherent synthesis of the most widely used mobility architectures, highlight their technological trade-offs, and formulate well-justified recommendations for selecting an optimal locomotion solution depending on the application domain. The practical contribution of this work lies in supporting the design and development of future mobile robot platforms intended for object transportation in industrial, medical, and commercial environments, building on prior work addressing cooperative lifting and transport of irregularly shaped payloads (Diaconu and Doroftei, 2025).

2. Classification of locomotion mechanisms

The locomotion mechanism is a fundamental component of any mobile robot, as it directly determines maneuverability, stability, energy efficiency, and safety in human-shared environments. The design choice of locomotion not only affects the robot's ability to transport objects efficiently but also its compliance with safety standards in collaborative operations (Siegwart *et al.*, 2011; Villani *et al.*, 2018).

Among the most deployed solutions are wheeled locomotion systems, which provide simplicity, reliability, and energy efficiency for structured indoor environments. Differential drive systems, consisting of two independently driven wheels and passive casters, are widely used for logistics and manufacturing applications due to their mechanical robustness and ease of control (Campion *et al.*, 1996; Dudek and Jenkin, 2010). Skid-steer or tank-drive robots, controlling wheels on each side collectively, allow in-place turning but require careful management of wheel slippage. In contrast, Ackermann steering mechanisms, inspired by automotive design, offer superior stability during high-speed motion while minimizing lateral slip, though the required turning radius can limit maneuverability in narrow spaces (Siegwart *et al.*, 2011).

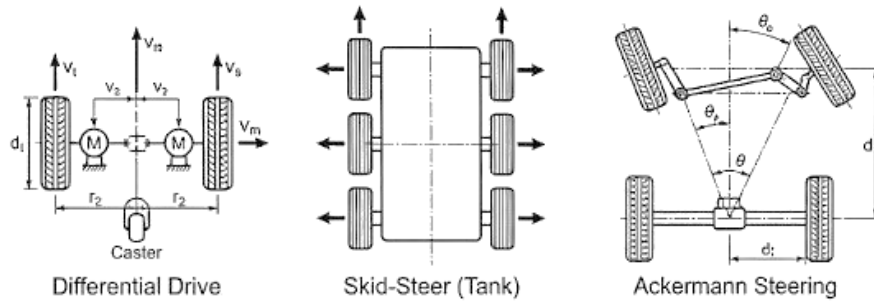


Fig. 1 – Wheeled robots locomotion mechanisms.

Moving from these conventional wheeled designs, omnidirectional platforms such as those equipped with mecanum or omniwheels allow motion in any planar direction without the need to change orientation. This capability provides a distinct advantage in confined or dynamic environments where precise lateral movement is necessary, such as hospitals, retail facilities, or areas with significant human traffic (Eirale *et al.*, 2025). While omnidirectional robots offer high maneuverability, they also introduce challenges related to wheel slippage, control complexity, and maintenance requirements. To address these issues, advanced designs with independent steering wheels or compliant wheels incorporating active suspension have been proposed, further improving adaptability and ride comfort in human-shared spaces (Siciliano and Khatib, 2016).

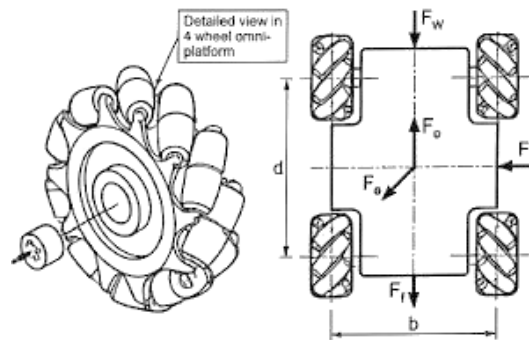


Fig. 2 – Omnidirectional robot locomotion mechanism.

While wheeled and omnidirectional systems dominate indoor applications, certain environments require tracked locomotion to cope with irregular or slippery surfaces. Robots equipped with continuous tracks distribute weight more evenly and achieve superior traction, which can be critical for handling heavier payloads or operating on uneven industrial floors (Dudek and Jenkin, 2010). However, tracked systems generally consume more energy and generate higher mechanical wear than wheeled alternatives, making them less

suitable for standard collaborative indoor environments. Hybrid wheel-track configurations have been explored to balance these trade-offs, offering adaptability in mixed-use settings (Wang *et al.*, 2021).

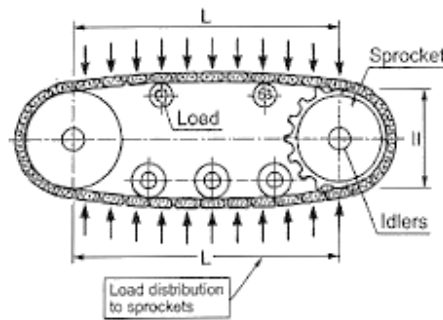


Fig. 3 – Tracked robot locomotion mechanism.

Beyond wheels and tracks, legged locomotion introduces capabilities that wheels alone cannot achieve. Bipedal, quadrupedal, and hexapodal robots can traverse highly irregular terrain, step over obstacles, and maintain stability on inclines or uneven surfaces. Concepts such as the support polygon, Zero Moment Point (ZMP), and dynamic balance are fundamental for designing legged systems capable of reliable and safe locomotion (Vukobratović and Borovac, 2004). Adaptive gait strategies further enhance versatility by allowing the robot to modify its stride and step patterns depending on terrain conditions. Despite these advantages, legged robots remain mechanically complex and energy-intensive, posing significant challenges for control and safety certification in collaborative settings.

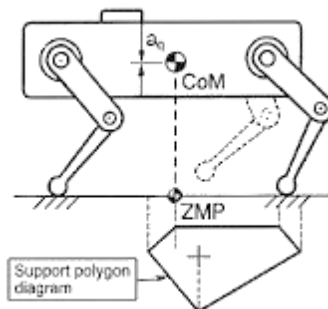


Fig. 4 – Legged robot locomotion mechanism.

Extending the spectrum of locomotion strategies, serpentine or snake-like robots offer yet another alternative. Using multiple articulated segments to generate undulatory motion, these robots excel at navigating narrow passages and cluttered or uneven environments (Dudek and Jenkin, 2010). Although their use

in collaborative indoor operations is limited, they provide valuable insights for specialized material handling, inspection, or confined-space exploration.

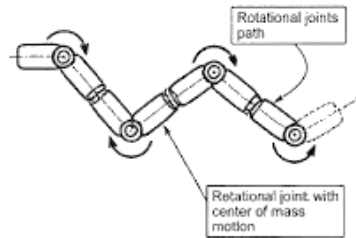


Fig. 5 – Serpentine robot locomotion mechanism.

In addition to serpentine designs, spherical or rolling robots, including ballbots and roller-bar mechanisms, represent unconventional approaches that rely on balance over one or more rolling contacts. These systems are inherently holonomic, enabling motion in any planar direction, and offer precise maneuverability. The challenge lies in maintaining continuous balance, which requires sophisticated control strategies and makes such systems primarily relevant for research and demonstration purposes (Siciliano and Khatib, 2016).

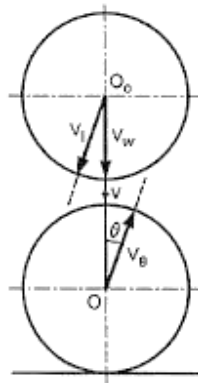


Fig. 6 – Spherical/Rolling robot locomotion mechanism.

Finally, hybrid and transformable locomotion systems integrate wheels and legs or other adaptive mechanisms to merge the advantages of multiple locomotion types. Robots such as OmniWheg combine omnidirectional wheels with leg extensions, allowing efficient navigation in constrained spaces while overcoming obstacles (Cao *et al.*, 2022). Experimental approaches in soft robotics or flying-wheel hybrids illustrate the ongoing exploration of new paradigms for collaborative mobility, highlighting future trends that may expand the versatility of mobile robots in diverse environments.

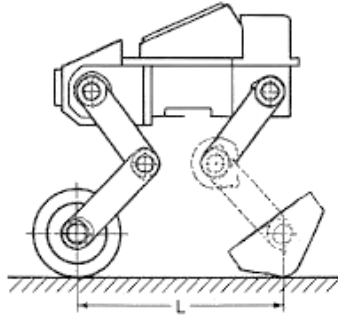


Fig. 7 – Hybrid robot locomotion mechanism.

The wide diversity of locomotion mechanisms used in mobile robots reflects the need to adapt robotic platforms to different operational environments and application requirements. Each locomotion architecture offers specific advantages and limitations in terms of maneuverability, terrain adaptability, energy efficiency, mechanical complexity, and safety during human–robot interaction. Therefore, selecting an appropriate mobility system requires a careful balance between performance, stability, payload capacity, and control complexity. To provide a clearer overview of these characteristics, Table 1 presents a comparative analysis of the most used locomotion mechanisms for mobile robots.

Table 1

Comparative classification of locomotion mechanisms for mobile robots

Locomotion mechanism	Mobility characteristics	Main advantages	Main limitations
<i>Differential drive</i>	<i>Non-holonomic; independent wheel actuation</i>	<i>Simple mechanical design; low cost; high reliability; efficient indoor navigation</i>	<i>Limited lateral motion; wheel slip affects odometry; reduced manoeuvrability in narrow spaces</i>
<i>Ackermann steering</i>	<i>Car-like steering geometry; large turning radius</i>	<i>High-speed stability; reduced lateral tire slip; smooth motion</i>	<i>Poor manoeuvrability in confined environments; larger turning radius</i>
<i>Omni-directional (Mecanum / Omniwheel)</i>	<i>Holonomic motion in any planar direction</i>	<i>Exceptional manoeuvrability; precise lateral movement; ideal for crowded environments</i>	<i>Wheel slip; vibration; complex kinematics; reduced payload efficiency</i>

<i>Tracked locomotion</i>	<i>Continuous ground contact using tracks</i>	<i>Excellent traction; high payload capability; good obstacle traversal</i>	<i>High energy consumption; mechanical wear; lower efficiency on smooth floors</i>
<i>Legged robots</i>	<i>Multi-DOF articulated locomotion</i>	<i>Superior obstacle negotiation; adaptable to irregular terrain</i>	<i>High mechanical and control complexity; low efficiency; expensive hardware</i>
<i>Serpentine robots</i>	<i>Undulatory segmented locomotion</i>	<i>Excellent manoeuvrability in confined spaces; adaptable body shape</i>	<i>Low transport speed; difficult control; limited payload capacity</i>
<i>Spherical and rolling robots</i>	<i>Motion through rolling shell or balancing mechanism</i>	<i>Compact structure; omnidirectional capability; smooth motion</i>	<i>Challenging balance control; limited payload; low industrial maturity</i>
<i>Hybrid and transformable systems</i>	<i>Combination of wheels, legs, or tracks</i>	<i>High versatility; adaptable to mixed environments; obstacle negotiation</i>	<i>Complex integration; high computational requirements; expensive systems</i>

In summary, locomotion mechanisms for mobile robots encompass a wide array of designs, each balancing maneuverability, energy efficiency, mechanical complexity, safety, and adaptability. Wheeled systems are predominant for standard indoor applications, omnidirectional platforms excel in confined human-shared environments, legged and hybrid robots are suited for terrain or obstacle-intensive scenarios, and experimental systems provide a vision of future capabilities. The optimal choice depends on the operational environment, payload requirements, human-robot interaction, and compliance with safety and performance standards (Siegwart *et al.*, 2011; Campion *et al.*, 1996; Dudek and Jenkin, 2010; Cao *et al.*, 2022).

3. Kinematic and dynamic modelling

The kinematic and dynamic modeling of mobile robots plays a pivotal role in understanding their motion capabilities, designing control strategies, and ensuring safe operation in human-shared environments (Siegwart *et al.*, 2011; Siciliano and Khatib, 2016). Accurate models allow engineers to predict robot

behavior under various operating conditions, guide the development of motion controllers, and support safety assessments in accordance with standards such as ISO/TS 15066 and ISO 3691-4. Mobility is not only a matter of mechanical design; it is intrinsically linked to control, perception, and safety, making modelling essential for both performance and regulatory compliance.

In indoor structured environments, wheeled configurations are predominant due to their simplicity and energy efficiency. Among these, differential drive robots represent a fundamental solution. With two independently driven wheels separated by a distance L and one or more passive casters, the forward velocity of the platform is given by:

$$v = \frac{(v_r + v_l)}{2} \quad (1)$$

The angular velocity is given by:

$$\omega = (v_r - v_l)/L \quad (2)$$

Where v_r and v_l denote the velocities of the right and left wheels, respectively (Campion *et al.*, 1996). The global planar position (x, y, θ) is then updated through:

$$\dot{x} = v \cos \theta, \dot{y} = v \sin \theta \quad (3)$$

$$\dot{\theta} = \omega \quad (4)$$

While this configuration offers mechanical robustness and simple control, it is constrained by non-holonomic motion and is susceptible to odometry errors on low-friction surfaces (Dudek and Jenkin, 2010).

For applications requiring higher speeds and improved stability, Ackermann steering provides an alternative by mimicking the steering geometry of automobiles. In this case, the front wheels turn at an angle δ , resulting in a turning radius:

$$R = \frac{L}{\tan \delta} \quad (5)$$

The angular velocity is:

$$\omega = \frac{v}{R} = v \frac{\tan \delta}{L} \quad (6)$$

This configuration, described by Eq. (5) and Eq. (6), enhances lateral stability and reduces slip at higher velocities, although the required turning radius can limit maneuverability in narrow spaces (Siegwart *et al.*, 2011). When precise motion in confined or dynamic environments is necessary, omnidirectional platforms offer significant advantages. Systems equipped with Mecanum or omniwheels allow holonomic motion, meaning the robot can move in any planar direction without changing its orientation (Alwan, 2020). The mapping from the robot's planar velocities (v_x, v_y, ω_z) to the individual wheel velocities $[v_1, v_2, v_3, v_4]^T$ is defined through a wheel distribution matrix J as:

$$v_\omega = J [v_x, v_y, \omega_z]^T \quad (7)$$

While offering unmatched maneuverability in spaces shared with humans, omnidirectional designs require precise control, may experience wheel slippage, and present greater mechanical complexity (Siciliano and Khatib, 2016). Compliant wheels and active suspension mechanisms have been proposed to mitigate these challenges and improve ride comfort.

Although wheeled and omnidirectional systems dominate indoor operations, certain environments demand specialized solutions to navigate uneven or slippery terrain. Tracked robots distribute the weight over continuous tracks, providing superior traction and enabling the handling of heavier payloads. Their forward velocity follows the same relation as in Eq. (1), while the angular velocity is given by Eq. (8):

$$\omega = (v_r - v_l)/L_{track} \quad (8)$$

While the dynamics of track-ground interaction introduce nonlinear friction forces that must be considered for precise control (Dudek and Jenkin, 2010; Wang *et al.*, 2021). Although energy consumption and wear are higher than in wheeled systems, tracks allow mobile robots to operate in more challenging indoor or semi-structured industrial settings.

Legged locomotion further extends the capabilities of mobile robots. Bipedal, quadrupedal, and hexapodal designs allow traversal of obstacles and uneven surfaces that wheeled or tracked systems cannot overcome. Joint kinematics are described by

$$P_i = f_i(q_i) \quad (9)$$

Here q_i represents the joint angles of the i -th leg. Stability is maintained using the support polygon and Zero Moment Point (ZMP), defined as:

$$ZMP_{x,y} = \frac{\sum_i (m_i g z_i - m_i \ddot{z}_i h_i)}{\sum_i m_i g} \quad (10)$$

Where m_i is the segment mass, z_i the vertical position, and h_i the horizontal moment arm (Vukobratović and Borovac, 2004). Adaptive gait strategies allow legged robots to respond to varying terrain, although their mechanical complexity and energy demands pose challenges for collaborative indoor environments.

Beyond legged platforms, serpentine robots employ multiple articulated segments to generate undulatory motion, enabling navigation through narrow passages and cluttered spaces. Segment positions follow Eq. (11) and Eq. (12):

$$x_i = x_{i-1} + l \cos(\theta_i) \quad (11)$$

$$y_i = y_{i-1} + l \sin(\theta_i) \quad (12)$$

While motion is controlled via serpenoid functions (Dudek and Jenkin, 2010):

$$\theta_i(t) = A \sin(\omega t + i\phi) \quad (13)$$

Although primarily suited for specialized or inspection tasks, serpentine designs provide insights into motion strategies in confined or complex environments.

Finally, hybrid or transformable robots integrate wheels and legs, combining the benefits of multiple locomotion types. Their effective velocity can be represented as:

$$v_{eff} = \alpha v_{wheel} + (1 - \alpha) v_{leg} \quad (14)$$

By $0 \leq \alpha \leq 1$ adjusting the contribution of each mechanism depending on the terrain (Cao *et al.*, 2022). Such platforms allow efficient navigation in constrained spaces while overcoming obstacles, highlighting the versatility of modern mobile robot designs. To provide a structured overview of these modelling approaches and their associated complexity, Table 2 summarises the key kinematic and dynamic properties of each locomotion type discussed in this section.

Table 2*Summary of kinematic and dynamic models for mobile robot locomotion*

Locomotion type	Model class	Constraint type	Main modelling challenge	Control complexity
<i>Differential drive</i>	Non-holonomic unicycle	Non-holonomic	Odometry drift on low-friction or slippery surfaces	Low
<i>Ackermann steering</i>	Bicycle (car-like)	Non-holonomic	Slip-angle estimation at speed; large minimum turning radius	Low
<i>Omni-directional (Mecanum)</i>	Holonomic planar	Holonomic	Roller-ground contact slip; vibration under lateral loads	Medium
<i>Tracked</i>	Non-holonomic + terrain friction	Non-holonomic and terrain shear	Track-soil interaction forces; real-time slip ratio estimation	Medium
<i>Legged</i>	Multi-DOF articulated + ZMP	Underactuated and hybrid	ZMP stability under variable payload; adaptive gait planning	High
<i>Serpentine</i>	Undulatory segmented	Redundant and over-actuated	Inter-segment friction coordination; redundant DOF control	Very High
<i>Hybrid (wheel-leg)</i>	Mixed holonomic and non-holonomic	Switching (mixed)	Mode-transition dynamics; real-time terrain classification	Very High

In summary, kinematic and dynamic modeling illustrates the trade-offs inherent to each locomotion mechanism. While differential drive and Ackermann steering excel in planar, structured environments, omnidirectional wheels dominate in confined human-shared spaces. Tracked systems facilitate heavier payload transport over irregular surfaces, legged robots negotiate complex terrain, and hybrid solutions offer flexible adaptability across diverse scenarios. The optimal locomotion mechanism must consider operational context, payload, human interaction, and compliance with safety standards (Siegwart *et al.*, 2011; Campion *et al.*, 1996; Dudek and Jenkin, 2010; Cao *et al.*, 2022).

4. Motion control and performance

Motion control represents the core functional layer of any mobile robot, as it transforms kinematic and dynamic models into safe, stable, and efficient

motion behaviors. For platforms designed to lift and transport objects of arbitrary shapes, this challenge becomes more pronounced due to the inherent variability of payload distribution, continuous shifts of the center of mass, and the strict safety requirements imposed by human–robot collaborative environments (ISO, 2023; Villani *et al.*, 2018). Motion control must guarantee not only accurate trajectory tracking but also compliance, robustness, and predictable dynamic behavior during close-proximity interaction with human operators (Siciliano and Khatib, 2016; Croft *et al.*, 2025). Therefore, selecting an appropriate control strategy requires balancing control performance, computational burden, implementation complexity, and the level of physical interaction expected between the robot and human operators. The main characteristics of the most relevant motion control strategies used in mobile robotic systems are summarized in Table 3.

Table 3
Comparative overview of motion control strategies for mobile robots

Control strategy	Computational cost	Performance profile	Implementation complexity	Suitable platforms
<i>PID / Linear feedback</i>	<i>Low</i>	<i>Good (structured envs)</i>	<i>Limited</i>	<i>All wheeled types</i>
<i>Backstepping / Lyapunov</i>	<i>Medium</i>	<i>Good (nonholonomic)</i>	<i>Moderate</i>	<i>Differential drive</i>
<i>Sliding-Mode control</i>	<i>Medium</i>	<i>Robust to disturbances</i>	<i>High</i>	<i>Wheeled, tracked</i>
<i>Model predictive control (MPC)</i>	<i>High</i>	<i>Excellent (constraints)</i>	<i>Moderate</i>	<i>All types</i>
<i>Impedance and admittance</i>	<i>Medium</i>	<i>Best for HRI compliance</i>	<i>High</i>	<i>Collaborative robots</i>
<i>Whole-Body control (WBC)</i>	<i>Very high</i>	<i>Optimal multi-DOF</i>	<i>High</i>	<i>Mobile manipulators</i>
<i>Reinforcement learning</i>	<i>Very high</i>	<i>Adapts to unknowns</i>	<i>Very high</i>	<i>Legged, hybrid</i>
<i>Neural adaptive control</i>	<i>High</i>	<i>Handles unmodelled dynamics</i>	<i>Very high</i>	<i>All types</i>

For differential-drive robots, nonholonomic constraints require advanced control strategies capable of compensating for geometric and dynamic limitations. While classical proportional–integral–derivative (PID) or linear feedback methods remain common, modern approaches rely heavily on nonlinear

control, backstepping, Lyapunov-based stabilization, and adaptive sliding-mode control, particularly when transporting payloads with unknown mass distribution (Campion *et al.*, 1996; Spong *et al.*, 2006). The presence of irregular objects induces parasitic torques that alter rotational dynamics, and adaptive controllers can estimate these disturbances online. Performance metrics for differential-drive platforms include steady-state trajectory error, robustness to wheel slip, and energetic efficiency under repetitive motion (Dudek and Jenkin, 2010). In many recent applications, model predictive control (MPC) has been introduced to handle velocity limits and safety constraints while maintaining smooth motion in human-shared spaces (Falcone *et al.*, 2007).

In omnidirectional platforms, the decoupling of translational and rotational motion simplifies trajectory planning but introduces complexity at the actuation and contact level. Mecanum and omniwheels generate lateral force components as a function of wheel roller geometry, leading to slip and non-ideal kinematics, especially under high loads (Alwan, 2020). Consequently, accurate motion control relies on extended kinematic models, wheel-ground interaction models, and real-time estimation of friction coefficients. Robust control strategies such as robust-MPC, disturbance observer-based control, and force distribution optimization are frequently employed (Terakawa *et al.*, 2019). Performance is evaluated through lateral tracking accuracy, vibration levels during sideways movement, and the system's ability to maintain orientation stability under dynamic loads or abrupt directional changes.

For hybrid mobile-manipulator systems, motion control becomes inherently multi-DOF and requires the simultaneous coordination of base motion, lifting mechanisms, and robot arms for object manipulation (Diaconu and Doroftei, 2025). In these systems, the dynamic coupling between the mobile base and the manipulated object becomes a significant factor. Whole-Body Control (WBC) and task-space impedance control are essential frameworks that distribute forces optimally among actuators while preserving balance and stability (Khatib *et al.*, 2018). When transporting heavy or irregular objects, WBC ensures that inertial forces generated by the payload do not destabilize the platform. Performance criteria include dynamic balance, object oscillation minimization, and compliance during unexpected external perturbations, which are fundamental in collaborative scenarios.

Platforms based on tracked locomotion require controllers tailored to the nonlinear interaction between tracks and ground. Models incorporate soil deformation, shear forces, and variations in contact pressure (Wong, 2008). Real-time terrain estimation derived from force sensors, inertial measurements, or data-driven terrain classifiers allows torque redistribution to maintain traction and avoid excessive slip. Adaptive control strategies help maintain stability while transporting large payloads or operating on rough industrial floors. Performance indicators include slip ratio stability, traction efficiency, and resistance to external disturbances such as uneven ground or sudden payload shifts (Cao *et al.*, 2022).

Legged robots, although less common in typical collaborative industrial environments, offer unmatched mobility for uneven or obstacle-rich terrain. Their motion control frameworks integrate Zero Moment Point (ZMP), centroidal momentum control, virtual model control, and quadratic-programming-based whole-body control to ensure dynamic stability while transporting variable payloads (Vukobratović and Borovac, 2004; Kuindersma *et al.*, 2016). When carrying irregular objects, these robots must continuously update gait parameters, including step length, support time, and foot placement, to compensate for shifts in the center of mass. Performance assessment involves criteria such as perturbation rejection, step stability, energy consumption per gait cycle, and capacity to maintain balance under external forces.

Recent advancements increasingly rely on machine learning and data-driven control. Reinforcement learning (RL) integrated with high-fidelity simulation environments enables robots to learn optimal motion policies that adapt to unknown payload dynamics (Hwangbo *et al.*, 2019). Gaussian Process Regression (GPR) and neural adaptive controllers enhance dynamic models by compensating for unmodelled effects, such as friction variation or payload oscillation. These strategies significantly improve performance robustness, making mobile robots capable of handling unexpected events such as sudden shifts in the object's weight distribution or environmental changes like wet floors.

The selection of locomotion mechanisms and motion control architectures is strongly influenced by the target application domain, operational environment, and safety requirements imposed on the robotic system. Different industries require specific trade-offs between maneuverability, payload capacity, terrain adaptability, positioning accuracy, and human-robot interaction capabilities. For example, industrial logistics prioritize efficiency and high payload transport, while healthcare and service robotics emphasize safety, precision, and smooth interaction in human-populated environments. Similarly, outdoor and unstructured applications such as agriculture, inspection, or search-and-rescue demand enhanced robustness, terrain adaptability, and autonomous navigation capabilities. Consequently, the choice of mobile platform and control strategy must be aligned with both environmental constraints and functional performance objectives. Table 4 summarizes the relationship between representative application domains, preferred locomotion mechanisms, key performance requirements, and dominant operational constraints.

Table 4
Application domains, preferred locomotion mechanisms, and dominant operational constraints

Application domain	Preferred mechanism	Key performance requirements	Main operational constraints
<i>Industrial logistics</i>	<i>Differential drive, Ackermann</i>	<i>High payload, speed</i>	<i>ISO 3691-4, tight schedules</i>
<i>Healthcare and hospitals</i>	<i>Omnidirectional (Mecanum)</i>	<i>Silent, safe, precise</i>	<i>ISO/TS 15066, hygiene</i>
<i>Retail and service spaces</i>	<i>Omnidirectional, differential drive</i>	<i>Crowd navigation</i>	<i>Human proximity, aesthetics</i>
<i>Agriculture</i>	<i>Tracked, wheeled hybrids</i>	<i>Rough terrain, autonomy</i>	<i>Weather, GPS-denied zones</i>
<i>Search and rescue</i>	<i>Legged, serpentine, tracked</i>	<i>Obstacle traversal</i>	<i>Reliability in extremes</i>
<i>Research and exploration</i>	<i>Hybrid, legged, spherical</i>	<i>Versatility, data collection</i>	<i>Energy limits, durability</i>
<i>Inspection (Pipes, Infra.)</i>	<i>Serpentine, tracked mini</i>	<i>Confined spaces</i>	<i>Size constraints, reliability</i>

The integration of advanced control models, robust optimization, hybrid control frameworks, and adaptive learning methods results in substantial improvements in motion performance. Modern mobile robots can now achieve predictable and stable motion while transporting objects of arbitrary shapes, maintaining compliance with safety standards, and adapting in real time to disturbances. These developments pave the way for wider adoption of mobile robots in logistics, industrial automation, healthcare, and service robotics, where adaptability, efficiency, and human safety are paramount.

5. Research gaps and future directions

Despite the significant progress achieved in mobile robot locomotion, motion control, and adaptive navigation, several important research challenges remain insufficiently addressed in current literature. Most existing robotic platforms are optimized for predefined operating conditions and structured environments, while real-world collaborative scenarios involve dynamic obstacles, uncertain payload distributions, varying floor conditions, and continuous human interaction. Furthermore, the increasing integration of artificial intelligence and learning-based controllers introduces additional concerns related to computational complexity, safety certification, explainability, and real-time reliability. Current control architectures often struggle to simultaneously guarantee adaptability, energy efficiency, and compliance with strict industrial safety standards, particularly in applications involving heavy or

irregular payload transportation. These limitations indicate the need for more robust, scalable, and human-aware control frameworks capable of operating safely in partially unstructured environments. Table 5 summarizes the main research gaps identified in the literature together with representative future research directions.

Table 5
Summary of critical research gaps

Research gap	Current limitation	Suggested approach
<i>Standardized benchmarks for locomotion evaluation</i>	<i>No universal comparison framework</i>	<i>Define reproducible metrics and test protocols</i>
<i>Energy efficiency in omnidirectional systems</i>	<i>Wheel slip increases consumption</i>	<i>Active roller control, adaptive gait planning</i>
<i>Long-horizon trajectory learning (RL)</i>	<i>Sim-to-real transfer gap remains large</i>	<i>Domain randomization, real-world fine-tuning</i>
<i>Safety certification for AI-based controllers</i>	<i>No ISO standard for learned controllers</i>	<i>Formal verification, constrained RL</i>
<i>Hybrid locomotion optimization</i>	<i>Sub-optimal mode switching strategies</i>	<i>Multi-objective optimization frameworks</i>
<i>Human intent prediction in shared spaces</i>	<i>Reactive control insufficient for crowds</i>	<i>Predictive social force models + RL</i>
<i>Payload-aware control at system level</i>	<i>Payload dynamics rarely modelled online</i>	<i>Online inertia estimation, adaptive WBC</i>

Future developments in mobile robotics will likely focus on the integration of adaptive control, artificial intelligence, real-time environment perception, and human-aware decision-making within unified robotic architectures. Hybrid locomotion systems, online payload estimation, and socially compliant navigation are expected to become central research directions for next-generation collaborative robots. Additionally, the development of standardized evaluation protocols and safety certification methodologies for AI-based controllers will play a crucial role in accelerating industrial adoption. These research directions are essential for enabling mobile robots to operate safely, autonomously, and efficiently in increasingly dynamic and human-centered environments.

6. Conclusions

The analysis presented in this paper provides a comprehensive overview of mobility in mobile robots, emphasizing locomotion mechanisms, kinematic and dynamic modelling, motion control strategies, and performance considerations. Mobile robots represent a transformative approach to automation in environments shared with humans, requiring the integration of mechanical

design, advanced control algorithms, sensor feedback, and strict adherence to safety standards (Siegwart *et al.*, 2011; Villani *et al.*, 2018).

From the classification of locomotion mechanisms, it is evident that no single solution is universally optimal. Wheeled systems, particularly differential-drive platforms, offer simplicity, robustness, and high energy efficiency for structured indoor environments, yet are limited by nonholonomic constraints and lower adaptability to complex terrain (Campion *et al.*, 1996; Dudek and Jenkin, 2010). Ackermann steering mechanisms improve stability at higher velocities but require larger turning radii, which may restrict manoeuvrability in confined spaces (Siegwart *et al.*, 2011). Omnidirectional platforms, such as mecanum and omniwheel robots, provide exceptional manoeuvrability and holonomic motion, making them suitable for dynamic, human-populated environments, though they demand more complex control strategies and careful management of wheel-ground interactions (Eirale *et al.*, 2025; Alwan, 2020). Tracked robots and legged robots expand operational capabilities to irregular, slippery, or obstacle-rich terrains, offering enhanced adaptability at the cost of higher energy consumption, mechanical complexity, and control demands (Wang *et al.*, 2021). Hybrid and transformable systems, such as OmniWheg, represent a promising avenue for combining the advantages of multiple locomotion paradigms while mitigating individual limitations.

Kinematic and dynamic modelling forms the backbone of accurate motion prediction and control. Precise representation of wheel or leg geometry, mass distribution, contact forces, and dynamic coupling with payloads enables the design of controllers capable of achieving desired trajectories under variable operating conditions (Spong *et al.*, 2006; Siciliano and Khatib, 2016). Motion control strategies, ranging from classical PID to advanced-nonlinear and model-predictive approaches, are essential to maintain stability, compensate for disturbances, and ensure safe interaction with human operators. Adaptive control, impedance/admittance methods, and learning-based approaches, such as reinforcement learning or neural adaptive control, further enhance the robot's ability to respond to unpredictable payload dynamics and environmental variability (Croft *et al.*, 2025; Hwangbo *et al.*, 2019).

Performance evaluation of mobile robots must consider maneuverability, energy efficiency, payload capacity, and compliance with safety standards (ISO, 2016; ISO, 2023). Each locomotion paradigm presents unique trade-offs: wheeled systems maximize efficiency in structured settings; legged and hybrid robots maximize versatility over complex terrains; and omnidirectional platforms maximize maneuverability in tight, human-shared spaces. These considerations are critical when designing mobile robots for specific applications, including intralogistics, healthcare, and retail, where operational reliability, human safety, and repeatable performance are paramount (Ivanov *et al.*, 2019; Sharma *et al.*, 2023).

In conclusion, mobile robot mobility is a multidimensional challenge that integrates mechanical design, control theory, sensing, and human-centered considerations. The choice of locomotion mechanism must be guided by the intended operational environment, payload requirements, safety considerations, and desired level of interaction with humans. Emerging trends in hybrid locomotion, adaptive control, and machine-learning-based motion strategies offer significant potential to expand the operational capabilities of mobile robots, enabling safe, efficient, and versatile mobile robotic systems. The insights provided in this work aim to support researchers, designers, and engineers in selecting and developing optimal mobility solutions for the next generation of mobile robots, ensuring both technological excellence and human safety.

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MECANISME DE MOBILITATE ȘI LOCOMOȚIE PENTRU ROBOȚI MOBILI

(Rezumat)

Lucrarea oferă o analiză cuprinzătoare a mecanismelor de mobilitate și locomoție ale roboților mobili, cu accent pe rolul acestora în medii dinamice, partajate cu oamenii. Este urmărită evoluția de la vehiculele ghidate automat clasice către platformele autonome capabile de interacțiune sigură cu operatorii umani, subliniindu-se caracterul multidisciplinar al mobilității, care îmbină proiectarea mecanică, controlul mișcării și conformitatea cu cerințele de siguranță. Articolul propune o clasificare detaliată a sistemelor de locomoție, acționare diferențială, direcție de tip Ackermann, roți omnidirecționale, șenile, roboți pășitori și configurații hibride, analizând avantajele, limitările și domeniile de aplicare specifice fiecăreia. Sunt prezentate, de asemenea, principiile de modelare cinematică și dinamică necesare pentru predicția și controlul precis al mișcării, precum și principalele strategii avansate de control, de la controlerele neliniare la controlul predictiv bazat pe model și abordările bazate pe învățare automată. În final, sunt discutate criteriile de performanță relevante, manevrabilitate, eficiență energetică, stabilitate și conformitatea cu standardele internaționale de siguranță.