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A Comprehensive Review of Four-Wheel Independent Drive and Steering Systems: Integrating Double Ackermann Kinematics, Advanced Trajectory Tracking, and Active Safety

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Abstract: The transition from conventional front-wheel steering to over-actuated four-wheel independent steering and driving architectures has fundamentally redefined the limits of robotic mobility in constrained environments. Among these configurations, the double Ackermann geometry has emerged as the optimal solution to minimize lateral slip and enable advanced non-holonomic maneuvers, such as pure lateral crabbing and zero-radius turning. However, the redundant degrees of freedom introduce severe complexities in multibody dynamic modeling and optimal torque allocation. This paper presents a comprehensive review of the scientific literature published between 2016 and 2026 regarding the modeling, trajectory tracking, and safety integration of these highly agile platforms. We deconstruct the mathematical foundations used in contemporary research, highlighting the application of Newton-Euler laws for high-fidelity 3-DOF and 7-DOF dynamic modeling and the utilization of Bolzman-Hamel theory to manage non-holonomic constraints through local quasi-velocities. Furthermore, we analyze the evolution of high-level control architectures, emphasizing the consolidation of linear time-varying model predictive control for handling hard actuator constraints, and the recent breakthroughs in deep reinforcement learning, specifically utilizing group intelligent experience replay to overcome sample inefficiency in continuous action spaces. The review also synthesizes critical low-level safety mechanisms, including load transfer ratio monitoring for active rollover prevention and fault-tolerant control for steer-by-wire systems. By correlating these theoretical advancements with field applications in precision agriculture, underground mining, and planetary exploration, this review provides a consolidated roadmap for addressing the remaining challenges in domain adaptation and real-time edge computing for the next generation of autonomous terrestrial systems.

Keywords Double ackermann · 4WS robots · Ackermann robots

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1 Introduction

The last decade has consolidated a disruptive transition in the morphology of robotic locomotion, shifting from conventional differential and simple Ackermann steering schemes toward over-actuated architectures of the four-wheel independent steering and independent driving type [1]. Historically, front-wheel steering systems have been constrained by a fundamental kinematic limitation: the instantaneous center of rotation must reside collinearly on the rear axle. This severely restricts agility in confined spaces and generates a strongly coupled dependency between lateral velocity and yaw rate at high speeds. To overcome this barrier, the double Ackermann geometry has emerged as an optimal solution. This configuration allows all four wheels to converge toward a dynamic instantaneous center of rotation that can be positioned arbitrarily in the two-dimensional plane, minimizing lateral side-slip and optimizing traction efficiency [2,3]. Furthermore, the capability to maintain precise trajectory tracking and minimize dynamic vibrations through this over-actuated geometry is no longer merely a locomotion objective, but rather a critical prerequisite for the reliable operation of advanced onboard payloads. As autonomous vehicles increasingly function as complex sensory and manipulation hubs, the kinetostatic stability of the mobile base directly dictates the efficacy of high-level cognitive tasks. For instance, the deployment of cutting-edge environmental perception architectures strictly demands a highly predictable kinematic platform to mitigate motion-induced sensor artifacts and spatial misalignment during complex maneuvers [4].

Unlike holonomic platforms based on Mecanum or classic omnidirectional wheels [5], which suffer from low load capacity and high susceptibility to terrain irregularities, the four-wheel independent steering and driving architecture preserves the robustness of traditional tire-road contact while expanding the control space. By providing redundant degrees of freedom through four independent steering angles and four independent driving torques, the system explicitly decouples the control of the chassis position from its orientation. This enables advanced non-holonomic locomotion modes, such as pure lateral displacement known as crabbing and rotation about the geometric center known as turn-in-place. These capabilities are critical in scenarios requiring high precision in constrained environments, such as high-density precision agriculture [6] and lunar exploration [7].

Although the superior maneuverability is evident, the over-actuation introduces a highly redundant control topology. The optimal distribution of contact forces at the tire-road interface becomes a multi-objective optimization problem. At high speeds, the nonlinearity of lateral friction, typically modeled using the Pacejka Magic Formula, causes traditional front-wheel steering systems to quickly reach a critical oversteer velocity. In contrast, the active control of rear steering in four-wheel steering platforms allows the modulation of the center of gravity side-slip angle toward zero, guaranteeing a significantly wider stability margin even on low-friction roads [8]. Achieving this degree of control, however, requires transitioning from idealized kinematic models to high-fidelity multibody dynamic models that can handle non-linear constraints in real time.

This review article provides a critical and exhaustive analysis of the scientific literature published between 2016 and 2026, focusing strictly on mobile robots utilizing the four-wheel independent steering and driving architecture with double Ackermann geometry. Unlike previous reviews that address autonomous navigation generically, this paper deconstructs the contemporary convergence between advanced dynamic modeling, particularly the Gibbs-Appell formulation, and upper-level control architectures. The scope encompasses strategies ranging from linear time-varying model predictive control to cutting-edge implementations in deep reinforcement learning, such as group intelligent experience replay and twin delayed deep deterministic policy gradient frameworks [9,10]. The primary objective is to establish a rigorous taxonomy of uncertainty mitigation and trajectory planning strategies, offering a consolidated theoretical foundation for the next generation of highly agile robotic locomotion systems.

2 Advanced Mathematical Foundations

The synthesis of robust controllers for four-wheel independent steering and driving platforms requires a mathematical representation that captures both the intrinsic geometric constraints of the undercarriage and the inertial forces of a multibody system. This section analyzes contemporary approaches to kinematic and dynamic formulation, highlighting the methodologies required for handling non-holonomic constraints.

2.1 Double Ackermann Geometry and Kinematic Constraints

The fundamental principle of the four-wheel steering kinematic model, when assuming parallel steering for the front and rear axles, relies on the simplification of the planar motion into a single-track or bicycle equivalent model. In this specific operational configuration, both the inner and outer wheels on the front axle are actuated to an identical steering angle, and a similar unified parallel actuation is applied to the rear axle wheels. For a vehicle with a total wheelbase l, which is divided into the distance from the center of gravity to the front axle a and to the rear axle b, the kinematic relationships must satisfy the zero lateral slip condition at the center of each axle. As illustrated in Figure 1, the global velocity vector V of the center of gravity, the side-slip angle beta, and the yaw rate gamma strictly dictate the required steering inputs to maintain a common instantaneous center of rotation.

Mathematically, by relating the lateral and longitudinal velocity components mapped from the center of gravity to the front and rear axles, the geometric constraint for pure rolling without lateral slip is expressed as:

$$\tan \delta_f = \frac{V \sin \beta + a\gamma}{V \cos \beta}, \quad \tan \delta_r = \frac{V \sin \beta - b\gamma}{V \cos \beta} \tag{1}$$

where the subscripts f and r represent the unified front and rear steering angles, respectively. This formulation directly links the vehicle's desired yaw rate and center of gravity side-slip angle to the physical actuator commands without requiring independent inner and outer wheel angle computations. Contemporary literature evidences that utilizing this parallel steering assumption significantly reduces the computational complexity of the control allocation layer. This approach

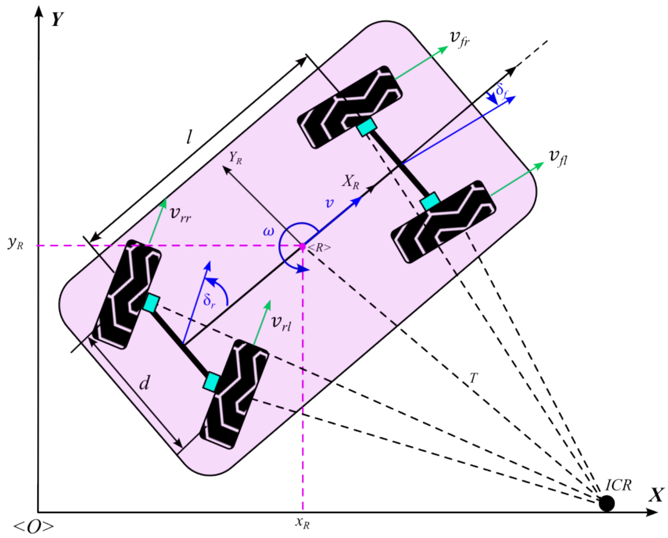

Fig. 1 Foundational kinematic architectures

allows for the direct algebraic mapping of the virtual control efforts to the steering mechanisms while still enabling advanced non-holonomic maneuvers, such as zero side-slip cornering and pure lateral displacement, provided that the vehicle operates within the linear tire friction region [2,11].

2.2 Jacobian Matrix Formulation for Logistic Trains

In intralogistics applications, these over-actuated robots frequently operate as traction units in logistic trains or continuous supply systems. The kinematic modeling of such articulated structures becomes intractable using purely trigonometric approaches. Recent studies have demonstrated the efficacy of utilizing Jacobian matrix-based formulations for these interconnected multibody systems [3]. The direct mathematical relationship to the double Ackermann geometry lies in the formulation of the non-holonomic constraint matrix. For a standard trailer with a fixed rear axle, the constraint matrix inherently causes a trajectory cut-in effect known as off-tracking. However, when the trailers are equipped with double Ackermann steering, the zero lateral slip constraints must be satisfied for both the front and rear steered axles simultaneously to maintain a common instantaneous center of rotation. Consequently, the elements of the Jacobian transformation matrix, which mathematically represents the null space of the constraint matrix, become explicit trigonometric functions of the four independent steering angles [10]. The general kinematic equation at the differential level is defined as:

$$\dot{q} = J(q, \delta)v, \tag{2}$$

where the term on the left is the time derivative of the generalized coordinate vector, the vector on the right contains the pseudo-velocities of the actuators, and the central matrix represents the Jacobian transformation matrix parameterized by the double Ackermann steering variables. This explicit inclusion of the double Ackermann geometry mathematically binds the velocity vector of the articulated unit to the trajectory curvature of the preceding tractor. This high tracking fidelity is paramount to completely mitigate the phenomenon of lateral off-tracking error amplification in narrow warehouse aisles [12].

2.3 Dynamic Modeling via Newton-Euler and Bolzman-Hamel Theories

Representing the vehicle through a simplified purely geometric or kinematic model based on Jacobian matrices and Ackermann distance relationships loses validity under high lateral accelerations and abrupt variations in terrain adhesion. To capture the true transient behavior of four-wheel independent steering platforms, the literature relies on multibody dynamic models. The historical and contemporary derivation of the equations of motion for both rotational and translational dynamics is predominantly achieved through the direct application of Newton-Euler laws. By explicitly balancing the external tire contact forces and the inertial moments acting on the center of gravity, researchers formulate robust analytical models [13,2]. This methodology is extensively applied to derive standard two-degree-of-freedom dynamic bicycle models for fundamental lateral control, as well as more complex three-degree-of-freedom models. The three-degree-of-freedom formulation explicitly captures the nonlinear coupling between longitudinal velocity, lateral velocity, and yaw rate, which is mathematically expressed as:

$$\begin{aligned} m(\dot{v}_x - v_y\gamma) &= \sum F_x \\ m(\dot{v}_y + v_x\gamma) &= \sum F_y \\ I_z\dot{\gamma} &= \sum M_z \end{aligned} \tag{3}$$

where m is the vehicle mass, Iz is the yaw moment of inertia, v_x and v_y are the longitudinal and lateral velocities, gamma is the yaw rate, and the right-side terms represent the sum of forces and moments generated by the four independent tires.

Furthermore, dealing with the non-holonomic constraints inherent to the moving reference frame presents analytical challenges when designing advanced model-based controllers. To manage the complex velocity transformations without relying on computationally heavy constraint multipliers, specific studies in the reviewed literature employ the Bolzman-Hamel theory [14]. This theoretical framework is utilized to formulate the linear equations of motion directly related to the quasi-velocities within the local coordinate system attached to the vehicle. By projecting the dynamics onto these quasi-velocities, the Bolzman-Hamel equations provide a mathematically rigorous yet streamlined representation of the system [14]. This approach significantly reduces the complexity of the dynamic matrices, facilitating the real-time execution of optimal control allocation algorithms and ensuring that the vehicle maintains kinetostatic stability even when the linear tire friction limits are approached.

3 High-Level Path Tracking Strategies

3.1 Geometric and Classical Control Evolution

The control architecture for four-wheel independent steering and driving platforms has transitioned from purely geometric algorithms to sophisticated optimization-based and robust control frameworks capable of handling high-speed dynamics and external disturbances. The fundamental pure pursuit algorithm, while computationally inexpensive, suffers from a critical limitation due to its fixed look-ahead distance, which causes either cutting corners at high speeds or oscillatory behavior on straight paths [15]. To address this, contemporary literature demonstrates the effectiveness of adaptive look-ahead mechanisms. For instance, fuzzy logic controllers have been utilized to dynamically adjust the look-ahead distance based on real-time lateral and heading deviations, significantly reducing tracking errors in agricultural machinery operating in unstructured environments [6,16]. Additionally, improved pure pursuit formulations that incorporate the derivative of the path curvature and real-time pose feedback have been shown to minimize steady-state tracking errors and improve the transient response of four-wheel independent steering robots [17]. While these geometric methods are adequate for low-speed kinematic tracking, longitudinal speed tracking is frequently decoupled and managed via expert proportional-integral-derivative controllers to simplify the overall control topology [18,2].

3.2 Optimal and Robust Control

As operational speeds increase and environmental interactions become highly nonlinear, geometric controllers fail to guarantee stability. Robust optimal control strategies have therefore become essential to mitigate parametric uncertainties, such as varying payload masses and tire cornering stiffness. H-infinity robust adaptive controllers have been successfully integrated into waypoint navigation systems for double Ackermann robots operating in orchard environments. This approach provides a mathematically guaranteed level of disturbance attenuation against sensor noise and terrain irregularities, ensuring that the lateral deviation remains bounded even under severe external perturbations [19]. By solving the associated Riccati equations, the H-infinity controller synthesizes a feedback gain matrix that minimizes the worst-case energy gain from the disturbance inputs to the regulated tracking errors.

3.3 Model Predictive Control and Adaptive Horizons

Despite the robustness of H-infinity methods, their inability to explicitly handle hard actuator constraints makes them suboptimal for highly constrained systems. Consequently, model predictive control has emerged as the benchmark for high-performance path tracking in over-actuated vehicles. Model predictive control formulates the tracking problem as a constrained multi-objective optimization over a finite receding horizon, allowing it to systematically manage steering angle limits and torque saturation. To alleviate the computational burden of solving nonlinear programs onboard, linear time-varying model predictive control is widely adopted. This technique linearizes the nonlinear multibody vehicle model around the reference trajectory at each sampling instant, transforming the optimization into a computationally tractable quadratic program [18,2]. The integration of advanced solvers, such as CasADi, enables the real-time execution of these predictive algorithms.

Furthermore, recent advancements have introduced adaptive mechanisms to the model predictive control framework, such as utilizing a multivariate Gaussian mixture model combined with ant colony optimization to dynamically tune the prediction horizon and weight matrices in response to changing environmental obstacles [10].

3.4 Nonlinear and Discontinuous Control

In scenarios characterized by sudden losses of tire adhesion or severe modeling mismatches, nonlinear discontinuous control methods are required to enforce trajectory convergence. Sliding mode control is frequently implemented in the upper-level coordination layer to compute the desired corrective yaw moment based on the lateral position and heading error dynamics [18]. However, the standard sliding mode control introduces high-frequency switching, known as chattering, which can excite unmodeled high-frequency dynamics and cause severe mechanical wear in steer-by-wire actuators. To overcome this limitation, higher-order sliding mode techniques, particularly the super-twisting algorithm, have been integrated into the trajectory tracking loops. The super-twisting algorithm provides a continuous control signal by hiding the discontinuous switching function under an integral, thereby completely eliminating chattering while preserving the exact finite-time convergence and absolute robustness against bounded matched uncertainties inherent to traditional sliding mode control.

4 Deep Reinforcement Learning in Motion Control

While model predictive control and sliding mode control offer robust mathematical guarantees, their reliance on accurate plant models makes them susceptible to unmodeled dynamics in extreme off-road or high-slip conditions [20]. Deep reinforcement learning has emerged as a powerful model-free alternative, capable of learning optimal control policies directly from complex, high-dimensional state spaces through continuous environmental interaction. For four-wheel independent steering and driving vehicles, deep reinforcement learning architectures are typically implemented within a compound control framework, serving either as an end-to-end trajectory tracker or as an auxiliary compensator that dynamically adjusts the parameters of a baseline classical controller.

4.1 **Sample Efficiency and Experience Replay Mechanisms**

The fundamental challenge in applying deep reinforcement learning to over-actuated platforms lies in the sheer dimensionality of the action space, which encompasses four independent steering angles and four independent driving torques. This high dimensionality exacerbates the issue of reward sparsity and sample skewness during the exploration phase. Traditional experience replay buffers randomly sample past transitions, which is highly inefficient when successful trajectory tracking events are rare. While hindsight experience replay mitigated this by substituting achieved goals for desired goals to maximize learning from failed episodes, it does not adequately address the skewed distribution of vehicle states in complex nonlinear maneuvers.

To resolve this, recent literature proposes the group intelligent experience replay mechanism [9]. The group intelligent experience replay algorithm applies non dominated sorting to the samples in the experience buffer, categorizing transitions based on tracking error metrics and temporal difference errors. By facilitating both within-group and between-group collaboration during the sampling process, this mechanism ensures a balanced distribution of training data. It effectively harmonizes the exploration and exploitation phases, preventing the policy from converging to suboptimal local minima and significantly accelerating the learning rate for complex double Ackermann kinematic maneuvers.

4.2 **Composite Actor-Critic Architectures and Information Bottlenecks**

Standard deep deterministic policy gradient algorithms frequently suffer from an overestimation bias in the Q-function, leading to brittle control policies that fail under real-world physical constraints. Therefore, the twin delayed deep deterministic policy gradient architecture, which utilizes two separate critic networks and delays the actor network updates, has become the preferred baseline for continuous control in four-wheel independent steering systems. However, feeding raw, high dimensional sensory data directly into these networks introduces severe feature redundancy. Variables such as sequential pose errors, tire slip angles, and varying terrain friction coefficients often contain overlapping information that degrades the generalization capability of the neural network.

To address the generalization problem in the complex nonlinear dynamics of these vehicles, researchers have integrated the principle of the information bottleneck into the actor-critic framework. Specifically, the two-stream information bottleneck method is employed to filter the state representations before they reach the decision layers [9]. By mathematically constraining the mutual information between the raw state input and the extracted latent representation, while simultaneously maximizing the mutual information between the latent representation and the target action, the information bottleneck effectively strips away redundant environmental noise. This extraction of compact, high-fidelity features allows the deep reinforcement learning agent to synthesize highly generalized steering and torque allocation commands, maintaining precise trajectory tracking even when the vehicle is subjected to previously unseen external disturbances.

5 Obstacle Avoidance and Motion Planning

The integration of obstacle avoidance mechanisms in four-wheel independent steering and driving platforms necessitates a delicate balance between immediate reactive behaviors and foresighted trajectory optimization [21]. The redundant degrees of freedom inherent in the double Ackermann geometry allow these vehicles to execute complex evasive maneuvers, such as lateral crabbing or zero-radius turns, which are physically impossible for conventional kinematic models. Consequently, motion planning architectures have evolved to explicitly leverage these capabilities, splitting the computational load between local reactive navigation stacks and global optimization-based evasion frameworks.

5.1 Reactive Navigation and Behavior Trees

In highly unpredictable environments, such as planetary surfaces or underground mines, relying solely on global path replanning is computationally prohibitive and practically unsafe due to the latency in sensor-to-actuator loops. To address this, contemporary research has widely adopted the Robot Operating System 2 and its advanced navigation framework, Nav2, to handle local reactive planning [7]. The transition from finite state machines to behavior trees in these navigation stacks provides a modular and highly responsive decision-making structure. Behavior trees allow the robot to evaluate sensory inputs in real time and asynchronously preempt current tasks to execute emergency maneuvers.

Recent implementations for lunar rovers demonstrate the efficacy of this approach by utilizing specialized maneuver servers within the ROS 2 ecosystem [7]. When a local costmap detects an imminent collision that cannot be bypassed via standard forward steering, the behavior tree triggers a mode-switching protocol. Depending on the spatial constraints and the surrounding regolith topology, the navigation stack dynamically reconfigures the four independent steering actuators to transition from standard double Ackermann steering to a crabbing mode for lateral evasion, or to a turn-in-place mode to completely reverse the heading. This reactive layer ensures survivability in unstructured terrain, although it primarily addresses immediate geometrical conflicts rather than holistic dynamic efficiency.

5.2 Optimization-Based Evasion in Predictive Horizons

While reactive navigation provides an essential safety net, high-speed maneuvers require obstacle avoidance strategies that account for the vehicle's multibody dynamics, tire friction limits, and actuator saturation. In these scenarios, reactive algorithms often fail to prevent loss of lateral stability or unrecoverable side-slip. Therefore, the state-of-the-art methodology formulates obstacle avoidance as an optimal control problem within a receding horizon framework, predominantly utilizing model predictive control.

In this architecture, static and dynamic obstacles are mathematically modeled as non-linear inequality constraints within the cost function of the model predictive controller. To maintain the computational tractability of the optimization problem, obstacles are typically represented by elliptical exclusion zones that expand based on the relative velocity and uncertainty covariance of the detected object. As the vehicle approaches an obstacle, the predictive solver evaluates the cost of deviating from the global reference path against the safety margins of the exclusion zones, computing the optimal independent steering angles and driving torques required to navigate the spatial bottleneck safely [10].

The real-time resolution of these highly constrained, non-convex optimization problems is facilitated by advanced algorithmic differentiation frameworks and non-linear programming solvers, such as CasADi. Furthermore, recent literature highlights the integration of meta-heuristic algorithms to dynamically tune the prediction horizon and weighting matrices of the model predictive controller. For example, utilizing a multivariate Gaussian mixture model combined with ant colony optimization allows the system to adaptively adjust its evasion aggressiveness [10]. In open spaces, the controller prioritizes energy-efficient path tracking, but upon detecting a dynamic obstacle, it autonomously shortens the prediction horizon and increases the penalty on constraint violations, ensuring a rapid and kineto-statically safe evasive trajectory without violating the fundamental double Ackermann geometric relationships.

6 Low-Level Control and Safety Integration

The successful execution of high-level trajectory commands in four-wheel independent steering and driving platforms relies heavily on the efficiency and reliability of the low-level control architecture. While upper-level controllers, such as the model predictive controller, compute the virtual generalized forces and the desired yaw moment required to track a path, the low-level layer is tasked with mapping these virtual demands onto the physical actuators. Due to the inherent over-actuation of the double Ackermann geometry, the system possesses infinite combinations of individual wheel torques and steering angles that can satisfy a given net force and moment requirement. Consequently, the low-level control is formulated as a constrained multi-objective optimization problem known as control allocation.

The primary objective of the torque allocation algorithm is to maintain tire forces well within the linear region of the friction circle while simultaneously minimizing the overall energy consumption of the drive motors. Traditional pseudo-inverse mapping methods are computationally fast but often fail to account for actuator saturation and dynamic variations in the tire-road friction coefficient. To address this, contemporary research has successfully implemented meta-heuristic algorithms for real-time optimal torque distribution. Specifically, the mutant particle swarm optimization algorithm has been utilized to solve the non-convex allocation problem. By introducing a mutation operator into the standard particle swarm optimization framework, the algorithm avoids premature convergence to local minima. This ensures an optimal distribution of driving and braking torques among the four wheels, which not only improves the overall energy efficiency but also maximizes the traction margin of each tire, thereby enhancing longitudinal and lateral stability during high-speed cornering [2].

As these autonomous platforms execute tight turning maneuvers enabled by the double Ackermann geometry, the resulting high lateral accelerations introduce severe safety risks, particularly for vehicles with a high center of gravity such as autonomous electric road sweepers and high-clearance agricultural sprayers. The prevention of un-tripped rollovers is mathematically quantified using the load transfer ratio. The load transfer ratio is defined as the normalized difference between the vertical reaction forces on the right and left tires. A value of zero indicates a perfectly balanced load, while a value approaching positive or negative one signifies imminent wheel lift-off. Advanced low-level safety integration involves continuously monitoring the predicted load transfer ratio. If the calculated index exceeds a predefined dynamic stability threshold, a rollover prevention intervention is triggered. This active safety layer seamlessly overrides the nominal path tracking commands by either distributing differential braking to rapidly reduce longitudinal velocity or actively reducing the front and rear steering angles to safely increase the radius of the instantaneous center of rotation [22, 8].

Furthermore, the physical decoupling of the steering wheel from the actuators in steer-by-wire systems necessitates robust fault-tolerant control strategies. In the event of a critical hardware or software failure, such as a steering actuator locking at a fixed angle or a drive motor losing power, the structural redundancy of the four-wheel independent steering and driving architecture allows for dynamic system reconfiguration. Fault-tolerant control algorithms detect the specific actuator anomaly and instantaneously update the kinematic Jacobian matrix and the dynamic stability domain bounds. The allocation layer then mathematically redistributes the required corrective yaw moment to the remaining functional wheels. By generating differential thrust and adapting the steering angles of the healthy actuators, the vehicle can actively compensate for the asymmetrical drag or locked geometry, ensuring the robot remains within the extension dynamic stability domain and can safely navigate to a maintenance point without catastrophic loss of control [18].

7 Field Applications and Sectoral Performance

The theoretical maturity of four-wheel independent steering and driving architectures, combined with the double Ackermann geometry, has catalyzed their deployment across industrial sectors characterized by highly restrictive and unstructured operational environments. In precision agriculture, autonomous navigation in high-density orchards and autonomous furrow tracking require exceptional maneuverability to minimize soil compaction and avoid mechanical damage to crops during headland turns. Recent literature demonstrates that integrating fuzzy logic and H-infinity robust adaptive controllers allows high-clearance agricultural machinery to maintain sub-centimeter trajectory tracking precision, actively compensating for severe nonlinearities introduced by varying soil moisture and external environmental disturbances [6, 19]. Furthermore, the reduced turning radius and the convergence toward a common instantaneous center of rotation inherent in this kinematic configuration resolve the critical issue of maneuvering space in greenhouses, thereby optimizing the cultivable area without compromising lateral stability.

In the underground coal mining sector, trackless auxiliary transport robots face the immense challenge of navigating through narrow, irregular tunnels with unpredictable friction profiles. For these heavy-duty applications, advanced dynamic modeling based on Gibbs-Appell formulations and coordinated trajectory tracking control are vital to prevent lateral collisions against gallery walls [13]. The ability of the over-actuated system to independently modulate the front and rear steering angles enables these vehicles to perform continuous heading corrections with minimal lateral chassis deviation, ensuring safe, stable, and high-capacity underground load transport.

Concurrently, modern manufacturing intralogistics demands multi-unit transport systems, commonly referred to as milk-run logistic trains, capable of operating at high speeds in increasingly narrow storage aisles. The application of Jacobian matrices to model the kinematics of multiple coupled trailers featuring double Ackermann steering ensures strict tracking fidelity relative to the tractor unit [3]. This kinematic precision completely mitigates the trajectory error amplification phenomenon, known as off-tracking, in each successive unit of the train, which is a fundamental safety factor for the total automation of high-density warehouses.

Finally, in the demanding field of space exploration, next-generation lunar and planetary rovers maximize the actuator redundancy of four-wheel independent systems to operate over extreme topologies and sinkage-prone regolith. By implementing reactive navigation architectures and maneuver servers based on the Robot Operating System 2, these rovers can dynamically switch between traditional locomotion modes and complex nonholonomic base maneuvers, such as pure lateral crabbing and turning on their own central axis [7]. These advanced capabilities not only facilitate reactive obstacle evasion in dead-end scenarios but also permit precise chassis orientation adjustments required for optimal solar energy collection and static stabilization on steep inclines. The technical convergence of all these field applications demonstrates that the addressed architecture transcends mere geometric agility, establishing itself as the de facto standard for solving extreme mobility challenges on a global scale.

8 Challenges and Future Directions

Despite the significant advancements in the control and modeling of four-wheel independent steering and driving systems with double Ackermann geometry, several open challenges remain for the next decade. A primary bottleneck is the simulation-to-reality gap in navigation over unstructured terrains. Although deep reinforcement learning architectures show exceptional results in simulated environments, their physical deployment in extreme conditions requires more robust transfer learning techniques. Domain adaptation remains fundamental to handle the stochastic nature of tire-soil interaction, especially in the presence of dense mud or lunar regolith where traditional tire models fail to predict traction accurately [9, 7].

Furthermore, a stark trade-off persists between computational efficiency and mathematical model fidelity. High-fidelity nonlinear dynamic formulations, particularly those derived from Newton-Euler laws or Bolzman-Hamel equations for quasi-velocities, provide superior analytical accuracy for over-actuated vehicles but demand onboard processing power that is often prohibitive for real-time applications in agricultural platforms or space rovers [7]. Future research must therefore focus on the development of edge artificial intelligence acceleration algorithms and hardware-in-the-loop optimization for model predictive control solvers. This is essential to enable the execution of complex optimization matrices in the kilohertz range, ensuring the stability of the vehicle during high-speed maneuvers on low-adhesion surfaces.

Finally, the integration of swarm intelligence and multi-agent coordination for over-actuated logistic trains represents an emerging scientific frontier. The decentralized coordination of multiple independent traction units requires solving coupled kinematic constraints based on complex Jacobian matrices to ensure path-following fidelity. The standardization of low-latency communication protocols within the robot operating system ecosystem will be pivotal to guarantee collision-free, scalable, and energy-efficient formation tracking at the industrial level [3, 2].

9 Conclusions

This review has systematically and critically analyzed the state of the art of mobile robots with four-wheel independent steering and driving operating under the double Ackermann geometry during the decade from 2016 to 2026. The transition from classical geometric steering control schemes toward highly over-actuated multibody dynamic systems has completely redefined the theoretical limits of robotic maneuverability and lateral stability. A key finding of this synthesis is the robust integration of Newton-Euler laws for 3-DOF and 7-DOF dynamic modeling, alongside the application of

Bolzman-Hamel theory to manage non-holonomic constraints via local quasi-velocities. These mathematical frameworks have proven essential for capturing the nonlinear coupling of the vehicle's chassis while maintaining computational efficiency for real-time control.

The literature indicates that linear time-varying model predictive control has consolidated as the superior mathematical framework for managing hard actuator constraints and system nonlinearities. Simultaneously, deep reinforcement learning, driven by advanced data sorting mechanisms such as group intelligent experience replay, is rapidly closing the sample efficiency gap required for decision-making in uncertain and unstructured terrains. The integration of low-level safety layers, specifically those focused on the continuous monitoring of the load transfer ratio and optimal torque allocation through metaheuristic optimization, has proven to be the enabling factor for the scientific viability of these platforms. By preventing kinetostatic catastrophes such as untripped rollover and ensuring recovery through fault-tolerant control in steer-by-wire systems, these technologies allow for safe deployment in critically demanding sectors ranging from precision agriculture to planetary exploration. As research advances toward fully autonomous ecosystems, the theoretical convergence of robust optimal control for disturbance rejection and high-fidelity dynamic modeling will undoubtedly dictate the design paradigms for the next generation of high-mobility terrestrial robotic systems.

Conflict of interest

The authors declare that they have no conflict of interest.

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