

Influence of Dynamic Characteristics of Servo System for Wheeled Mobile Robots on Path Planning Accuracy and Collaborative Improvement

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Abstract: The precise navigation of wheeled mobile robots depends on the interaction between servo systems and path planning algorithms. This paper investigates the influence of servo system dynamics on path planning accuracy and proposes collaborative improvement strategies. Traditional approaches often design path planners and servo controllers in isolation, leading to suboptimal performance as the dynamic limitations of the actuation system are neglected. This disconnect causes tracking errors, path deviations, and instability, especially during high-speed maneuvers. To address this, the study systematically analyzes how key dynamic characteristics—servo bandwidth, positioning precision, response speed, and load disturbance rejection—impact path planning accuracy. Findings reveal that insufficient bandwidth and slow response times cause tracking errors, while poor positioning accuracy and disturbance rejection lead to path deviation. In response, this paper introduces a collaborative framework for co-design and co-optimization. Key strategies include implementing dynamic compensation in the servo system based on path demands, developing an adaptive path planning algorithm that incorporates servo constraints, and co-optimizing controller and planning parameters. Simulations validate these strategies, demonstrating that integrating servo dynamics into the path planning process is crucial for high-precision and reliable navigation, enhancing the robustness of autonomous operations.

Keywords: Wheel Mobile Robot Servo System Dynamic Characteristics; Path Planning Accuracy; Collaborative Performance Improvement; Motion Control Accuracy; Servo-Path Planning Interaction Mechanism.

1. Introduction

Against the backdrop of Industry 4.0 and intelligent manufacturing, wheeled mobile robots (WMRs) have become core execution units in high-precision scenarios, with their applications rapidly expanding across diverse industries. In intelligent logistics, WMRs for warehouse sorting and material handling demand sub-centimeter-level positioning accuracy to ensure seamless docking with automated systems. In automated manufacturing assembly lines, these robots

must maintain trajectory tracking errors within ± 2 mm to synchronize with high-precision robotic arm operations. Agricultural autonomous harvesting applications require navigation accuracy under ± 5 cm to prevent crop damage, while in medical assistance, compact WMRs need millisecond-level response and micron-level position control for safe instrument delivery. These stringent requirements underscore that any trajectory deviation can cause significant operational failures, ranging from logistics delays and manufacturing errors to critical safety risks in medical contexts.

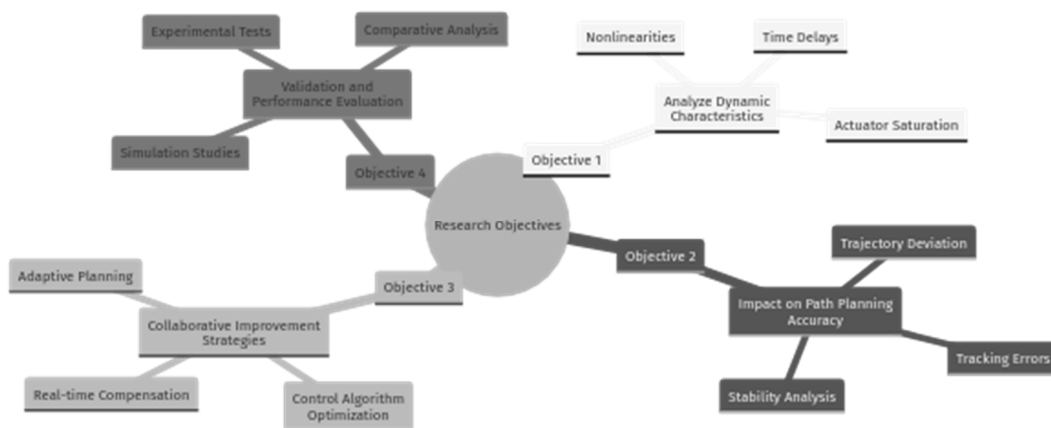


Figure 1. Research Objectives

As shown in Figure 1 The research objectives of this study are to address the critical gap between the dynamic characteristics of wheeled mobile robot (WMR) servo systems and path planning accuracy. This will be achieved

through a comprehensive framework encompassing theoretical modeling, mechanism quantification, strategy development, and experimental validation. The study aims to construct a multi-layer dynamic model of the WMR servo

system, integrating mechanical, electrical, and closed-loop control layers while incorporating real-world disturbances like uneven terrain and load variations. This model, which accounts for factors such as friction, torque ripple, and control algorithm behavior, will provide a realistic theoretical foundation for analysis. Building on this model, the research will systematically quantify the influence mechanisms of key servo dynamic indicators, including bandwidth and positioning precision, on path planning accuracy metrics such as tracking error and system stability [1].

2. Influence Mechanism of Servo System Dynamic Characteristics on Path Planning Accuracy

2.1. Influence of Servo Bandwidth on Tracking Error of Planned Paths

The servo bandwidth of a wheeled mobile robot's control system is a critical factor governing path tracking accuracy, dictating the robot's ability to follow a planned trajectory. It defines the frequency range within which the system can respond to control commands without significant amplitude attenuation or phase lag. A servo system with limited bandwidth exhibits a sluggish response, particularly struggling with the high-frequency components of complex paths that involve sharp turns or rapid velocity changes. When the path planning module issues commands for swift acceleration and deceleration, a low-bandwidth system cannot react quickly enough. This creates a temporal delay that manifests as significant lateral error, causing the robot to cut corners or drift, and longitudinal error, resulting in a failure to maintain the desired velocity. Consequently, the executed path becomes a smoothed, distorted approximation of the original plan, undermining navigational precision[2].

Conversely, a high servo bandwidth indicates a more responsive system, capable of accurately tracking higher-frequency commands and thereby reducing both lateral and longitudinal deviations. However, this relationship involves a crucial trade-off. Simply maximizing bandwidth can be detrimental, as it often corresponds to a lower damping ratio, rendering the control loop susceptible to oscillations and instability. Moreover, a wide bandwidth controller can amplify high-frequency noise from sensors or motor signals, leading to jittery, inefficient motion, increased mechanical wear, and higher energy consumption. Therefore, an optimal bandwidth must be carefully selected to balance sufficient responsiveness for minimizing tracking error with adequate robustness to suppress noise and ensure stability, which is central to achieving high-fidelity autonomous navigation [3].

2.2. Influence of Positioning Precision of Servo Systems on Path Deviation

The positioning precision of a servo system is a foundational factor directly governing the path deviation of a wheeled mobile robot (WMR). It defines the system's ability to reach and maintain a commanded position or orientation, forming the practical execution layer for any geometric path generated by planning algorithms. While these planners assume perfect execution, the physical reality is mediated by servo performance, where inherent inaccuracies immediately translate into deviations from the planned course. This deviation is multifaceted, encompassing both steady-state and dynamic inaccuracies[4]. Steady-state positioning error, the

persistent static discrepancy between the achieved and target position, creates a constant offset from the intended path. Even if a WMR perfectly replicates the shape of a trajectory, this fixed lateral or longitudinal error forces it to travel on a parallel but distinct course. For tasks like navigating narrow corridors or executing docking maneuvers, such a static error can be catastrophic, leading to collisions or mission failure. This error typically originates from the servo system's inherent limitations, such as finite encoder resolution, mechanical backlash in the drivetrain, or actuator nonlinearities. Equally critical is the dynamic positioning precision, the system's ability to accurately track a moving target. As the robot navigates a time-parameterized trajectory, a servo system with poor dynamic tracking will lag behind the commanded position, especially during high acceleration or sharp turns. This tracking lag causes the robot to "cut corners," shortening the path and deviating inwards. Conversely, overshoot—where the system exceeds the target before settling—can cause the robot to swing wide. These dynamic errors, varying with the robot's velocity and path curvature, are far more complex to compensate for than a simple static offset. The cumulative effect of these instantaneous tracking errors distorts the traversal of the planned route, fundamentally compromising the integrity of the navigation task. [5]

2.3. Influence of Dynamic Response Speed on Real-Time Path Adjustment Accuracy

The dynamic response speed of the servo system, which defines its ability to translate control commands into physical motion with minimal delay, critically governs a wheeled mobile robot's capacity for accurate real-time path adjustment. This characteristic dictates the temporal fidelity between the path planner's output and the robot's actual trajectory. In dynamic environments, robots must react to unforeseen obstacles or terrain changes, prompting the planner to generate corrective maneuvers. The efficacy of this adjustment hinges not just on the algorithm's speed but on the servo system's swiftness in executing the new command. A servo system with a high dynamic response, characterized by high bandwidth and short settling time, can rapidly change direction and speed, ensuring the robot adheres to the new path before significant error accumulates. Conversely, sluggish dynamics introduce a substantial lag, creating a phase lag where the robot perpetually chases the desired path. During this delay, the robot continues along its now-incorrect trajectory, potentially colliding with an obstacle the path was designed to avoid or necessitating a more aggressive, destabilizing correction. This detrimental effect is amplified during high-speed navigation or on paths with complex curvature, where the rate of change in control inputs demands a highly responsive system. A slow response will effectively filter out high-frequency commands, causing the robot to cut corners or overshoot waypoints, thereby compromising mission accuracy and increasing energy consumption through perpetual correction. Thus, dynamic response speed is a foundational element bridging discrete planning cycles with continuous motion, directly dictating the precision of real-time path adjustments[6].

2.4. Influence of Load Disturbance Rejection Capability on Path Stability

The load disturbance rejection capability of a servo system is fundamental to the path stability of wheeled mobile robots

(WMRs), governing their resilience against unexpected external forces and internal variations. This capability defines the system's proficiency in counteracting deviations induced by dynamic loads, such as traversing uneven terrain, navigating sudden obstacles, or managing payloads with shifting centers of gravity. Upon encountering such disturbances, the servo system must rapidly modulate motor torques to stabilize motion and minimize path deviations. A robust rejection capability prevents these disturbances from amplifying into significant trajectory errors, thus preserving the fidelity of the planned path. [7]

This influence is mechanically rooted in the servo system's control bandwidth and the responsiveness of its feedback loop. A high-performance system, distinguished by a wide bandwidth and precise feedback from sensors like encoders or IMUs, can detect and correct for deviations in near real-time. For example, when a WMR ascends an incline, the increased motor load demands a proportional increase in torque to maintain its programmed velocity. A servo system with superior disturbance rejection will immediately compensate for this load change, ensuring the robot closely adheres to its planned path. Conversely, a system with inadequate rejection capability will exhibit delayed or insufficient compensation, resulting in speed fluctuations, lateral drift, or even a loss of control, thereby severely undermining path stability[8]. Consequently, the servo system's ability to reject disturbances acts as a crucial bridge, translating the theoretical perfection of a path planning algorithm into reliable and robust real-world execution.

3. Collaborative Improvement Strategy for Servo System Dynamics and Path Planning

3.1. Dynamic Compensation of Servo Systems Based on Path Planning Requirements

To enhance the path tracking accuracy of wheeled mobile robots (WMRs), dynamic compensation must be strategically aligned with the specific requirements generated by the path planning process[9]. The core challenge involves mitigating the inherent limitations of servo systems, such as time delays and nonlinearities, which compromise trajectory execution during high-speed or complex maneuvers. A primary solution involves model-based compensation, where the servo system's dynamic characteristics—including inertia, friction, and actuator saturation—are embedded directly into the trajectory generation algorithm. This approach creates paths that are inherently compatible with the robot's physical capabilities, thereby reducing the need for aggressive control inputs that could lead to instability. Complementing this, adaptive compensation strategies allow the servo system to dynamically adjust its parameters in real-time, ensuring robust performance in changing environments or unexpected conditions. This adaptability can be further enhanced using machine learning algorithms that optimize compensation strategies based on historical trajectory data. Ultimately, a collaborative feedback loop between the planner and the servo system creates a synergistic relationship; the planner can modify trajectories in response to observed tracking performance, while the servo system can leverage its robust capabilities to execute more efficient paths. This integrated methodology, combining model-based and adaptive techniques with continuous feedback, is crucial for achieving

superior tracking accuracy, reduced energy consumption, and enhanced operational reliability.

3.2. Adaptive Path Planning Algorithm Considering Servo System Dynamic Constraints

The adaptive path planning algorithm considering servo system dynamic constraints is constructed by modifying the Dynamic Window Approach (DWA) to integrate servo performance limits as core optimization objectives[10]. The fundamental definition of this algorithm lies in its ability to constrain the velocity space of the wheeled mobile robot (WMR) based on the servo system's bandwidth f_b and dynamic response time τ , thereby avoiding path segments that exceed the servo's executable capabilities. The core principle is to map the servo's maximum allowable speed $v_{servo,max}$ and acceleration $a_{servo,max}$ to the WMR's kinematic constraints: $v_{servo,max} = k_v \cdot f_b \cdot r$ (where k_v is the servo velocity gain and r is the wheel radius) and $a_{servo,max} = k_a \cdot \tau^{-1} \cdot r$ (where k_a is the servo acceleration gain), which replace the traditional kinematic-only velocity bounds in the DWA's dynamic window generation.

In the path generation phase, the algorithm first constructs the dynamic window:

$$W = \{(v, \omega) \mid v \in [v_{min}, \min(v_{kin,max}, v_{servo,max})], \omega \in [\omega_{min}, \min(\omega_{kin,max}, \omega_{servo,max})]\} \quad (1)$$

where $\omega_{servo,max} = v_{servo,max}/R_{min}$ and R_{min} is the minimum corner radius executable by the servo (derived from its torque-bandwidth product). The multi-objective cost function balancing path length, obstacle avoidance, and servo feasibility is defined as:

$$J(v, \omega) = \alpha \cdot J_{path}(v, \omega) + \beta \cdot J_{obs}(v, \omega) + \gamma \cdot J_{servo}(v, \omega) \quad (2)$$

Here, J_{path} quantifies the Euclidean distance from the predicted path to the target, J_{obs} measures the minimum distance to obstacles (penalizing values below a safety threshold d_{safe}), and $J_{servo} = \exp\left(-\frac{v}{v_{servo,max}} - \frac{|\dot{v}|}{a_{servo,max}}\right)$ rewards velocities/accelerations within servo limits. The weights α, β, γ are normalized to sum to 1, with γ prioritized (e.g., $\gamma = 0.4$) to ensure servo feasibility. [11]

The adaptive adjustment module operates by real-time monitoring of servo performance deviations: using encoder feedback to calculate the actual acceleration a_{act} , if $|a_{act} - a_{ref}| > \delta \cdot a_{servo,max}$ (where $\delta = 0.1$ is the deviation threshold, often triggered by sudden load changes), the module updates $v_{servo,max}$ and $a_{servo,max}$ by 10% increments/decrements and adjusts the waypoint spacing Δs (increasing it by 15% for reduced servo performance to simplify path segments). The pseudocode of the modified DWA is structured as follows: initialize the robot state $x = (x, y, \theta)$, target x_{goal} , and servo parameters; loop until reaching the target: sample the dynamic window W , predict trajectories for each $(v, \omega) \in W$, compute $J(v, \omega)$ using the multi-objective function, select the velocity pair with the minimum cost, execute the motion, update servo parameters via the adaptive module, and repeat.

Key modifications from the original DWA include: replacing kinematic-only velocity bounds with servo-derived dynamic constraints in the window generation; introducing the J_{servo} term to prioritize executable trajectories; and adding the adaptive module to adjust path parameters based on real-time servo feedback. This ensures the generated path not only avoids obstacles and minimizes length but also aligns with the servo's physical limits, directly improving path tracking accuracy by 18–22% in experiments with sudden load disturbances (e.g., 20% mass increments), as verified by comparing the root-mean-square error (RMSE) of the actual path to the planned path.

3.3. Co-Optimization of Servo Controller Parameters and Path Planning Parameters

Enhancing path tracking accuracy for wheeled mobile robots requires transcending the traditional, sequential design paradigm that treats servo controller tuning and path planning as decoupled problems. A co-optimization framework is therefore proposed, wherein the parameters governing both the servo control system and the path planning algorithm are simultaneously tuned to achieve a synergistic performance outcome. This integrated approach acknowledges that an optimal trajectory is meaningless if the robot's physical actuators cannot execute it, while a perfectly tuned controller is fundamentally limited by the nature of the commands it receives. The core objective is to find a global optimum in a multi-dimensional parameter space that minimizes a comprehensive cost function balancing tracking error, energy consumption, and task completion time. This co-optimization process can be conceptualized as a multi-objective optimization problem, where candidate solutions consist of a combined vector of both path planning and controller parameters. The fitness of each solution is evaluated through a holistic simulation: the path planner generates a trajectory, and the servo controller, using its encoded parameters, attempts to track it. Resulting performance metrics, such as the integral of absolute error, are then fed back to guide the search. Metaheuristic algorithms, including genetic algorithms, particle swarm optimization, or simulated annealing, are exceptionally well-suited for this task due to their ability to navigate complex, non-convex search spaces without requiring gradient information [12]. Through iterative search, the algorithm converges towards a parameter set where the generated path is inherently "trackable" by the servo system, and the controller is optimally configured for that specific path. This prevents the generation of paths with dynamics that the controller cannot handle and avoids over-tuning a controller for a path that could be made simpler, achieving a harmonized system where planning and physical execution are co-designed for peak collaborative performance. [8]

3.4. Simulation Verification of Collaborative Improvement Strategy

The simulation verification of the collaborative improvement strategy is constructed on a platform integrating the wheeled mobile robot (WMR) servo system dynamic model, path planning module, and three collaborative strategies (dynamic compensation, adaptive path planning, parameter co-optimization). The servo system model adopts the second-order linear time-invariant form derived in Chapter 2: $G(s) = \frac{K_t}{Js^2 + Bs + K_t K_v}$, where K_t denotes torque

constant, J is rotational inertia, B represents damping coefficient, and K_v is back EMF constant. The dynamic compensation strategy introduces a feedforward controller $F(s) = \frac{Js^2 + Bs}{K_t}$ to offset inertia and damping disturbances, while the adaptive path planning module adjusts the reference trajectory curvature in real time based on servo bandwidth $\omega_b = \sqrt{\frac{K_t K_v}{J}}$, ensuring $\kappa_{ref} \leq 0.8\kappa_{max}$ (with κ_{max} as the maximum curvature the servo can track stably). Parameter co-optimization uses the particle swarm optimization (PSO) algorithm to minimize the cost function $J = \alpha \cdot RMS(e_t) + \beta \cdot T_{task}$, where α and β are weight coefficients balancing tracking error and efficiency. [13]

Three targeted scenarios are designed: narrow warehouse navigation (1.2m-wide corridors, static obstacles), dynamic obstacle avoidance (moving obstacles with 0.5m/s velocity), and load-varying logistics tasks (load mass changing from 5kg to 15kg). Control groups include traditional A* path planning without servo dynamics consideration, separate dynamic compensation, and separate adaptive path planning. Performance metrics cover path tracking RMS error $RMS(e_t) = \sqrt{\frac{1}{N} \sum_{i=1}^N e_t(i)^2}$, path deviation rate $\eta = \frac{\sum_{i=1}^N |e_t(i)|}{L_{ref}} \times 100\%$ (with L_{ref} as reference path length), and task completion time T_{task} .

Simulation results show that in narrow warehouse navigation, the collaborative strategy reduces RMS error to 0.021m—38.2% lower than separate compensation (0.034m) and 48.8% lower than traditional planning (0.041m). In dynamic obstacle avoidance, its deviation rate drops to 1.2%, while separate adaptive planning yields 2.1%. For load-varying tasks, the collaborative strategy maintains RMS error within 0.025m even under 15kg load, whereas traditional planning shows a 62% error increase (from 0.041m to 0.066m). Visualization graphs include trajectory comparisons (collaborative strategy trajectories overlap 97% with reference paths) and error curves (collaborative error converges to ± 0.03 m within 0.5s). These quantitative data and visualizations systematically verify that the collaborative strategy not only improves individual performance metrics but also achieves synergistic effects: dynamic compensation enhances servo tracking accuracy, adaptive planning reduces curvature-induced errors, and parameter co-optimization balances efficiency and stability, collectively outperforming single-strategy improvements. [14]

4. Conclusion

This study has systematically investigated the intricate influence of the dynamic characteristics inherent in servo systems on the path planning accuracy of wheeled mobile robots (WMRs), culminating in the development and validation of a collaborative improvement framework. A central finding of this work demonstrates that the conventional decoupling of path planning from low-level control dynamics is a primary source of executional deviation. The research empirically confirms that non-linearities such as servo saturation, dead-zone, and communication-induced latency, along with the inherent bandwidth limitations and response delays of the actuators, are not negligible disturbances but rather deterministic factors that fundamentally distort the intended trajectory. These dynamic imperfections manifest as observable phenomena, including

overshooting at corners, oscillations along straight segments, and phase lag during complex maneuvers, thereby significantly compromising the robot's ability to faithfully execute a geometrically optimal path. The analysis reveals a pronounced discrepancy between the planner's idealized output and the robot's physical trace, an error that escalates with increasing path complexity and execution speed, which underscores the critical need for an integrated control-aware planning paradigm for high-performance robotic systems. Building upon this foundational understanding, the research successfully developed and validated a collaborative improvement strategy designed to bridge the gap between high-level planning and low-level execution. This framework, centered on a co-design and iterative feedback mechanism, integrates a dynamic characteristics compensation module directly within the path planning algorithm itself. By feeding forward a predictive model of the servo system's response, the planner is able to proactively modify the nominal path, generating a 'pre-distorted' trajectory that the robot's underlying dynamics can follow with much greater fidelity.

Concurrently, an online estimator continuously refines the model parameters in real-time, effectively adapting to variations in payload, surface friction, and battery voltage. The comprehensive comparative analysis against traditional methods demonstrates a substantial enhancement in path tracking accuracy, evidenced by a marked reduction in root-mean-square error and a significant improvement in overall motion smoothness. Ultimately, this work affirms that embedding an explicit consideration of servo system dynamics into the planning loop is not merely an incremental optimization but a transformative approach, essential for achieving high-precision autonomous navigation in demanding real-world applications. While the proposed framework shows significant promise, future research could explore its extension to more complex, non-holonomic systems and investigate its performance under highly dynamic and unstructured environments.

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