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# A review of path tracking control methods for wheeled mobile robots

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**Abstract.** With the rapid advancement of technology, wheeled mobile robots have been increasingly widely applied in industrial production, logistics transportation, service sectors, and even daily life. Trajectory tracking accuracy is critical for achieving autonomous navigation and efficient operations. Traditional Proportional-Integral-Differential (PID) control controllers often exhibit limited tunability and inadequate disturbance rejection capabilities when dealing with system nonlinearities and external disturbances. This paper systematically reviews the research progress in path tracking control for wheeled mobile robots over the past five years, drawing on existing literature and empirical data. First, based on kinematic models, existing methods are categorized into four major categories: "classical PID-based", "intelligent PID-based," "Model Predictive Control (MPC)-based," and "data-driven." Their research advancements in tracking accuracy and disturbance rejection capabilities are analyzed. Through the classification and synthesis of relevant research, the paper identifies bottlenecks including complex ground disturbances and dynamic target tracking. It highlights that improvements in PID control primarily proceed along three directions: adaptive parameter tuning to enable automatic adjustment; intelligent algorithm fusion to enhance processing capabilities while maintaining simplicity; and enhanced disturbance rejection capabilities to guarantee reliability in practical applications. This review provides a roadmap for subsequent research and engineering selection.

**Keywords:** wheeled mobile robot, path tracking control, PID control, Model Predictive Control (MPC)

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## 1. Introduction

In recent years, China has successively put forward the development strategies of "Made in China 2025" and "Manufacturing Powerhouse Initiative" [1]. The core objective is to advance the transformation and upgrading of the manufacturing industry and realize the transition from a manufacturing giant to a manufacturing powerhouse. In this grand blueprint, robot technology, as a key pillar of advanced manufacturing, plays a pivotal role. In enhancing the intelligence level of the manufacturing industry, research achievements such as path planning and trajectory tracking control of wheeled mobile robots can significantly enhance the level of automation and intelligence in industrial production. Wheeled mobile robots exhibit broad application prospects in industrial automation, logistics transportation, intelligent transportation and other fields [2]. The key core technologies that determine the intelligence of wheeled robots include path planning and path tracking. However, in practical applications, existing path planning and trajectory tracking algorithms still have certain limitations in terms of computational efficiency, convergence and tracking accuracy. This study conducts a comprehensive review of the advancements in trajectory tracking control for wheeled mobile robots over the past five years, drawing on existing literature and empirical data. Initially, utilizing kinematic models as a basis, existing control methods are classified into four primary categories: "classical PID-based", "intelligent PID-based", "Model Predictive Control (MPC)-based", and "data-driven". Their research advancements in tracking precision and disturbance suppression capabilities are examined.

## 2. Evolution of PID control methods

### 2.1. PID control

PID control (proportional-integral-differential control) is a core control strategy in classical control theory. Owing to its simple structure, clear physical meaning, and ease of engineering implementation, it has been widely applied in industrial control, robot systems, and process control fields. The PID controller calculates the error between the system output and the desired value in real time, and conducts comprehensive adjustment based on the three components of error: proportion (P), integration (I), and differentiation (D), thereby achieving continuous and precise control of the controlled plant. Its control law can be expressed in the time domain as follows [3]:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt \quad (1)$$

Among them, $e(t) = r(t) - y(t)$ denotes the error between the setpoint $r(t)$ and the actual output $y(t)$; $K_p$, $K_i$, $K_d$ are the proportional, integral, and derivative gain coefficients respectively. In PID control, the proportional term directly reflects the magnitude of the current error and enables rapid response to system deviations; however, excessive gain tends to induce overshoot or system oscillation. The integral term eliminates steady-state errors via the cumulative effect of historical errors, improving the tracking accuracy of the system, but excessive integration can result in response lag and integral saturation phenomena. The derivative term adjusts according to the variation trend of errors, which can suppress overshoot and improve system stability; however, it is sensitive to measurement noise and may introduce high-frequency disturbances.

Traditional PID control belongs to integer-order control strategies, and its parameters $K_p$, $K_i$, $K_d$ are typically tuned through empirical methods, trial-and-error approaches, or classic methods such as Ziegler-Nichols. However, during the actual operation of wheeled mobile robots, the system is frequently subjected to model uncertainties, external disturbances, and environmental nonlinearities. Fixed-parameter PID controllers struggle to maintain superior control performance under complex dynamic conditions. Particularly in the presence of continuous or random disturbances, the dynamic response and anti-disturbance capability of traditional PID control are significantly limited, potentially resulting in increased tracking errors, prolonged adjustment time, and even affecting the stability of trajectory tracking [4].

Therefore, while PID control performs well in systems without disturbances or with simple structures, in trajectory tracking tasks for wheeled mobile robots with high requirements for control accuracy, response speed, and anti-disturbance ability, it is imperative to introduce intelligent control mechanisms with online parameter self-tuning capabilities (such as fuzzy reasoning, and neural networks) to enhance the robustness and adaptive performance of the system in complex environments. This also lays a necessary theoretical foundation and practical basis for the subsequent research on fuzzy fractional-order PID control.

## 2.2. Intelligent PID control method

Jin Yan et al. addressed the challenge of PID parameter tuning difficulty in path tracking of wheeled robots caused by model uncertainty and time-varying parameters. They proposed a fuzzy self-tuning PID control method based on a two-degree-of-freedom dynamic model and constructed a fuzzy rule base to online adjust PID parameters. The simulation validation was conducted in MATLAB/SIMULINK. The results showed that this method reduced the system error by approximately 20%, shortened the response time to 40% of the traditional PID, and significantly enhanced the dynamic performance and adaptive capability of path tracking [5].

To enable wheeled mobile robots to follow a preset target trajectory, Qian conducted research by constructing a planar model and establishing a dynamic model of the wheeled mobile robot [6]. They improved the traditional PID controller using fuzzy rules and adjusted the PID controller parameters online based on fuzzy theory, ultimately determining the optimal control parameters for the wheeled mobile robot. The specific research process is as follows: The author established the robot kinematic model, designed the fuzzy rule library, and used MATLAB simulations to compare the performance of traditional PID and fuzzy fractional-order PID under different disturbance conditions. The research results indicated that in a disturbed environment, the fuzzy fractional-order PID control error remained within $\pm 0.8\times10^{-3}$m, the adjustment time was shortened to 0.25s, and its performance was significantly superior to that of the traditional PID controller.

Recent research has started to explore the combination of reinforcement learning and PID control. By providing residual compensation via reinforcement learning, the PID controller achieves enhanced adaptability and robustness.

## 2.3. Advanced control methods: Model Predictive Control (MPC)

Model Development

MPC is an advanced control strategy based on the dynamic model of the object, which is particularly suitable for addressing complex systems with multiple variables, nonlinearity, and constraints, such as the trajectory tracking problem of wheeled mobile robots (Wheeled Mobile Robot, WMR). The fundamental principle of MPC can be encapsulated as three core components: "predictive model, rolling horizon optimization, and feedback correction." At each sampling instant, the controller predicts the future evolution of the system based on the current system state and the established model, and derives a sequence of optimal control inputs by solving a constrained optimization problem; Subsequently, only the first control input in the optimized sequence is applied to the controlled plant, and the updated system state is utilized to re-execute the prediction and optimization process, thereby realizing the rolling horizon optimization mechanism in closed-loop control.

In the trajectory tracking control of wheeled mobile robots, a prediction model is usually constructed based on their kinematic model. Taking the research of Xu et al. as an example, the kinematic model of WMR is first formulated: where denotes the pose of the robot in the global coordinate system, and is the control input (linear velocity and angular velocity).

To further improve control precision, a state error model was incorporated in relevant studies. The tracking error is defined as follows:

$$\mathbf{X}_e(t) = \begin{bmatrix} x_e(t) \\ y_e(t) \\ \theta_e(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{2}$$

In the formula, $(x_r, y_r, \theta_r)$ represents the expected pose on the reference trajectory. By linearizing the aforementioned error model or directly retaining its nonlinear structure, MPC can predict the system's error evolution over the next several steps within each control cycle, and comprehensively incorporate factors including tracking precision, control smoothness, and energy efficiency into the optimization objective function.

To ensure the stability and feasibility of the control system, various constraints are often introduced in the MPC optimization problem, including input constraints (such as amplitude limits of linear velocity and angular velocity), state constraints (such as position and attitude ranges), and terminal constraints. In the design proposed by Xu et al., by appropriately configuring the terminal penalty matrix $P$ and the terminal domain $\Omega$, and integrating Lyapunov stability theory, the asymptotic stability of the closed-loop system within a finite time horizon is rigorously proven. This thus theoretically guarantees the reliable execution of trajectory tracking [7].

Compared with traditional PID control, MPC exhibits distinct advantages in addressing multi-input multi-output systems, explicitly processing various constraints, and coping with nonlinear dynamics. It is particularly well-suited for trajectory tracking and navigation tasks of mobile robots in dynamic environments. Nevertheless, MPC also is confronted with challenges such as heavy online computational burden and strong dependence on model accuracy. Therefore, in real-time demanding scenarios, strategies such as model simplification and optimization algorithm acceleration often need to be combined for improvement.

## 2.4. Intelligent control methods

Neural Network (NN)-based control is a data-driven intelligent control strategy featuring autonomous learning and adaptive capabilities, which is particularly suitable for complex systems with model uncertainties and strong nonlinear dynamic behaviors. Compared to traditional control methods relying on accurate mathematical models, neural networks can learn from system input-output data, approximate and compensate for unknown dynamics and external disturbances online, and thereby remarkably improve the robustness and environmental adaptability of the controller.

To further improve the trajectory tracking precision and autonomous obstacle avoidance capability of wheeled mobile robots in complex dynamic environments, Zhou et al. proposed an advanced strategy integrating neural networks and model predictive control, namely neural network nonlinear model predictive control [8]. The core idea of this method is to incorporate a Multi-Layer Feedforward Neural Network (MLFNN) into the framework of conventional Nonlinear Model Predictive Control (NMPC) to dynamically approximate and compensate for predictive model errors induced by model simplification, parameter perturbations, and environmental disturbances.

Specifically, the constructed neural network typically comprises an input layer, multiple hidden layers, and an output layer. The input variables are selected as the system's state tracking error vector, including the planar position errors $e_x$, $e_y$, and the heading angle error $e_\theta$, and may also incorporate historical control information to enhance dynamic memory. The network output is either the estimated value of the model deviation within the predictive time horizon or directly functions as the compensation term for the control input. Through online or offline training procedures, the network weights are continuously updated to enable learning and internalization of the system's dynamic characteristics under disturbances and obstacle influences, thus realizing self-optimization of controller parameters and environmental adaptability.

To validate the effectiveness of the NN-NMP method, three representative test scenarios were designed on the MATLAB/Simulink simulation platform: an ideal trajectory tracking scenario without obstacles, a path tracking scenario with static obstacles, and a complex operation scenario with dynamic disturbances. For each scenario, comparative simulations were conducted between traditional PID control and the proposed NN-NMPC method, and key performance indicators including trajectory tracking error, obstacle avoidance success rate, response time, and control input smoothness were recorded [9].

The simulation results demonstrate that in the obstacle-free scenario, both control methods can achieve stable tracking of the desired trajectory with comparable control performance; however, when static or dynamic obstacles are introduced, traditional PID control, due to its absence of forward optimization and online learning mechanisms, can achieve basic obstacle avoidance but the trajectory deviation significantly increases and the control process exhibits oscillations; in contrast, the NN-NMP method, by leveraging the online error compensation capability of NNs and the rolling horizon optimization of model predictive control, successfully avoids obstacles while maintaining low tracking errors, demonstrating superior comprehensive control performance, stronger anti-interference ability, and excellent environmental adaptability.

In summary, NN-NMPC effectively improves the trajectory tracking precision and intelligent obstacle avoidance capability of WMRs in uncertain environments, offering a reliable technical solution for the autonomous navigation of WMRs in complex scenarios.

## 3. Technical analysis

Although substantial advancements have been made in current research, there are still many critical challenges that need to be solved urgently in the field of path planning and path tracking control for wheeled mobile robots.

(1) Insufficient robustness of path tracking in complex environments

In practical engineering applications, WMRs often encounter intricate environmental perturbations, such as uneven ground, time-varying friction coefficients, and obstacle disturbances. These uncertainties substantially degrade the accuracy and stability of path tracking. Conventional control methods exhibit inadequate adaptability to environmental variations, struggling to maintain satisfactory control performance in unknown or dynamic settings.

(2) Limited real-time tracking capability for dynamic targets

Traditional path-following control is predominantly designed for static target trajectories, whereas real-world missions involve paths that dynamically alter over time (e.g., moving targets, obstacle avoidance re-planning). Existing control strategies demonstrate tracking error divergence when target trajectories undergo abrupt or frequent variations, failing to strike a balance between real-time performance and control stability [10].

The advancement of PID control primarily evolves along the following directions:

Adaptive Parameter Tuning, achieving automatic parameter adjustment;

Intelligent algorithm integration, preserving structural simplicity while enhancing processing capabilities;

Improvement of anti-interference ability, guaranteeing operational reliability in practical applications.

## 4. Conclusion

From conventional PID to intelligent adaptive PID control, the control performance has been remarkably enhanced. Despite the attainment of tangible outcomes in existing research, numerous unresolved critical issues still persist in the field of path planning and trajectory tracking control for WMRs. In practical engineering applications, robots often face intricate environmental variables, like uneven terrain, fluctuating friction coefficients, and obstruction interference. Existing control methodologies exhibit tracking error divergence when target trajectories undergo abrupt or frequent variations, failing to reconcile real-time responsiveness with control stability. Future research may focus on the application of deep reinforcement learning to the self-tuning of PID parameters, developing a universal adaptive framework, and promoting the engineering implementation of advanced PID control strategies.

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