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REVIEW ARTICLE

A Mini Review of Control Technologies for Wheeled Mobile Robots Under Different Operating Conditions

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Abstract

Wheeled mobile robots are widely used in intelligent logistics, unmanned delivery, industrial inspection, service robots, and other fields due to their simple structure, flexible mobility, and low energy consumption. However, during actual operation, robots often encounter complex operating conditions such as tire slip, model uncertainty, input saturation, and external disturbances, which can lead to reduced trajectory tracking accuracy or even system instability. In recent years, scholars in China and abroad have proposed numerous advanced control methods for the control problems of wheeled robots under different operating conditions, including sliding mode control, disturbance observer-based control, adaptive control, finite-time control, and model predictive control. This paper reviews the control problems of wheeled robots under ideal conditions, slip conditions, input-constrained conditions, and complex disturbance environments. It analyzes the development status, typical algorithms, and future trends of control methods in recent years. Finally, the development directions of wheeled robot control technologies are summarized and discussed.

Keywords: wheeled mobile robot, trajectory tracking, sliding mode control, disturbance observer, input saturation, robust control.

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1 Introduction

With the development of intelligent manufacturing and artificial intelligence technologies, wheeled mobile robots (WMRs) have become an important component of modern intelligent equipment. Owing to their compact structure, high motion efficiency, and relatively simple control implementation, they have been widely used in warehousing and logistics, unmanned transportation, medical services, industrial inspection, and other fields, with trajectory tracking control performance directly determining their operational effectiveness in such applications [1].

However, wheeled mobile robots are typical nonlinear systems with nonholonomic constraints, and their motion control problems are highly complex. In practical environments, robot operation is often affected by factors such as tire slip, changes in ground friction, model parameter uncertainties, and actuator constraints, which lead to increased trajectory tracking errors. In particular, on complex ground surfaces, robots are prone to longitudinal slip and lateral skidding, making it difficult for traditional control methods to meet the requirements of high-precision and highly robust control [2].

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In recent years, advanced control methods based on sliding mode control, disturbance observers, finite-time control, and intelligent algorithms have gradually become research hotspots [3–5]. Finite-time control can ensure the rapid convergence of system errors within a finite time, while disturbance observers can estimate external disturbances in real time and provide online compensation, thereby significantly improving system robustness [6]. Meanwhile, intelligent control methods such as model predictive control, fuzzy control, and neural network control have also been gradually applied to the field of wheeled robot control [7, 8].

2 Kinematic and Dynamic Models of Wheeled Mobile Robots

Wheeled mobile robots typically adopt a differential-drive structure, and their pose state can be expressed as:

$$q = [x, y, \theta]^T \tag{1}$$

where x and y are the position coordinates of the robot, and θ is the heading angle. Under ideal pure rolling conditions, its kinematic model can be written as:

$$\dot{x} = v\cos\theta, \quad \dot{y} = v\sin\theta, \quad \dot{\theta} = \omega \tag{2}$$

where v is the linear velocity and ω is the angular velocity.

However, in complex ground environments, tire slip may occur in wheeled robots, resulting in inconsistency between the theoretical motion model and the actual motion state. The slip ratio is commonly used to describe the degree of tire slipping:

$$\lambda = \frac{v - r\omega}{\max(v, r\omega)} \tag{3}$$

where λ is the slip ratio, v is the theoretical translational velocity computed from wheel encoder readings, r is the wheel radius, and ω is the wheel's angular velocity (distinct from the robot's body angular velocity defined in Eq. (2)).

At the dynamic level, the robot system can generally be expressed as:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + d \tag{4}$$

where $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the Coriolis matrix, $G(q)$ is the gravity term, τ is the control input, and d represents external disturbances.

3 Control Methods Under Ideal Operating Conditions

3.1 PID Control

PID control is one of the most classical control methods for wheeled robots, and its control law is given by:

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \dot{e}(t) \tag{5}$$

PID control has a simple structure and is easy to implement in engineering practice; therefore, it has been widely applied in industrial robot control. However, PID control relies heavily on the system model and is prone to overshoot and oscillation problems in complex environments [2].

3.2 Backstepping Control

Backstepping control achieves step-by-step stabilization of the system by constructing virtual control inputs, and can effectively address **nonholonomic** constraint problems. This method has a solid basis for stability analysis, but it depends strongly on model parameters.

In recent years, **backstepping** control has often been combined with sliding mode control to improve system robustness. Huang and Gao [1] proposed a trajectory tracking method based on the combination of backstepping and a novel sliding mode control strategy, which improved the tracking performance of wheeled mobile robots.

4 Control Methods Under Slip Conditions

4.1 Sliding Mode Control

Sliding mode control (SMC) has been widely applied in the field of wheeled robot control because of its strong robustness against parameter perturbations and external disturbances [4].

A typical sliding surface is designed as:

$$s = \dot{e} + ce \tag{6}$$

By designing a switching control law, the system states can converge to the sliding surface within a finite time.

Although conventional sliding mode control has strong disturbance rejection capability, it is prone to chattering. To address this problem, researchers have proposed terminal sliding mode control and nonsingular fast terminal sliding mode control (NFTSM). Nguyen and Kim [4] proposed a fixed-time prescribed-performance sliding mode control method, which effectively improved the control accuracy of robots under wheel slip and external disturbance conditions.

4.2 Finite-Time Control

Finite-time control can ensure the convergence of system errors within a finite time, and therefore has important application value in highly dynamic robotic systems.

Miranda-Colorado [3] proposed an observer-based finite-time control method, achieving high-precision trajectory tracking in the presence of kinematic disturbances. Experimental results showed that this method still exhibits good robustness under measurement noise and external disturbances.

5 Disturbance Observation and Robust Control

5.1 Disturbance Observer

Disturbance observers (DOBs) can estimate unknown disturbances online based on system input and output information and provide real-time compensation [6].

Their basic form is:

$$\hat{d} = L(x - u) \tag{7}$$

where $\hat{d}$ is the estimated disturbance. Guo [6] proposed a fixed-time disturbance observer-based control method, which effectively compensated for wheel slip, lateral skidding, and parameter uncertainties.

5.2 Active Disturbance Rejection Control

Active disturbance rejection control (ADRC) has been widely applied in the field of wheeled robot control in recent years. Abadi et al. [5] proposed a trajectory tracking method based on differential flatness and sliding mode active disturbance rejection control, achieving high-precision control under wind disturbances and wheel slip conditions.

6 Control Under Input Saturation Conditions

During high-speed operation, the motor speed and driving torque of a robot are subject to physical constraints, thereby causing input saturation problems [7].

Input saturation may lead to:

1. system overshoot;
2. integral windup;
3. trajectory oscillation;
4. reduced stability.

In recent years, anti-windup control has gradually become a research hotspot, and its modified form is generally expressed as:

$$\dot{I} = e + K_{cw}(u_{sat} - u) \tag{8}$$

In addition, model predictive control (MPC) has also been widely used for trajectory tracking control under constraints. Relevant studies addressing robot trajectory tracking under skidding and time-varying delay have similarly highlighted the importance of explicitly accounting for system dynamic constraints to maintain tracking accuracy [2]; building on this need, MPC-based approaches can effectively handle input constraints and system dynamic constraints [7].

7 Intelligent Control Methods

7.1 Fuzzy Control

Fuzzy control can handle system uncertainties and reduce dependence on the system model. In recent years, the combination of fuzzy control and sliding mode control has become an important research direction [10].

Ding et al. [10] proposed a trajectory tracking method based on adaptive fuzzy control, which effectively improved the trajectory tracking performance of robots in the presence of external disturbances.

7.2 Neural Network Control

Neural networks can approximate complex nonlinear functions and are therefore widely used to compensate for model uncertainties and unknown disturbances.

In recent years, methods combining neural networks with sliding mode control and finite-time control have gradually increased, effectively improving control performance in complex environments [8, 9].

8 Future Development Trends

The future development directions of control technologies for wheeled mobile robots mainly include:

1. **Multi-sensor fusion control** UWB, IMU, vision, and LiDAR can be integrated to achieve high-precision state estimation, providing more accurate disturbance and kinematic

information to support robust trajectory tracking controllers such as differential flatness-based active disturbance rejection schemes [5].

2. **Integration of intelligent and robust control** Sliding mode control, adaptive control, and neural networks can be combined to improve robustness under complex operating conditions [8, 9].

3. **Model predictive and constraint control** Further improvements can be made in trajectory tracking performance under input-constrained conditions.

4. **Finite-time and predefined-time control** The rapid convergence capability of the system can be enhanced to achieve higher dynamic performance.

5. **Autonomous adaptive control for complex terrains** Research on wheel-ground interaction mechanisms can be carried out for sandy, icy, snowy, and rugged terrains.

9 Conclusion

Control technologies for wheeled mobile robots have gradually evolved from traditional PID control to sliding mode control, disturbance observer-based control, and intelligent control. To address problems such as slip disturbances, input saturation, and complex environments, methods proposed in recent years, including finite-time control, disturbance observer-based control, and model predictive control, have significantly improved system stability and trajectory tracking performance.

In the future, with the development of artificial intelligence, multi-sensor fusion, and high-performance computing technologies, wheeled robot control systems will develop toward higher intelligence, stronger robustness, and greater adaptability to complex environments, providing important technical support for intelligent manufacturing, unmanned transportation, smart services, and other fields.

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Ethical Approval and Consent to Participate

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