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Robust adaptive tracking control of wheeled mobile robot

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HIGHLIGHTS

- Tracking control for a wheeled mobile robot is achieved by finite-time control.
- The disturbance observer gives an accurate compensation for system uncertainty.
- Requirement of boundary information of system uncertainty can be released.

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ABSTRACT

This paper considers the problem of robust adaptive trajectory tracking control for a wheeled mobile robot (WMR). First, the trajectory tracking of the WMR is converted to a problem of the stabilization of a double integral system. Next, a continuous finite-time control method is employed to design a tracking controller. Then, a disturbance observer and an adaptive compensator are designed to cooperate with the tracking controller for dealing with system uncertainties of the WMR. Finally, a switching adaptive law is presented in combination with the boundary layer approach to attenuate the chattering in the adaptive compensator. As a result, the control system yields the ultimate boundedness of both the tracking error and the adaptive gain. Simulation results demonstrate the validity of the new method.

1. Introduction

A wheeled mobile robot (WMR) is a typical kind of nonholonomic systems. The design of a robust control system is a difficult task due to the nonlinearities and uncertainties in the system, and has been attracting a great attention [1,2].

Tracking control for a WMR not only requires a designed controller to track a prescribed orbit, but also has to robustly stabilize the closed-loop system against the system uncertainties. The existing control methods include the nonlinear control methods, artificial intelligent methods, visual servoing control, etc. The nonlinear control methods contain backstepping method [3], sliding mode control (SMC) [4–6], and finite-time control technique [7]. And the adaptive compensation is further incorporated with the above methods to make the control system more practical [8]. For example, Jiang and Nijmeijer presented a backstepping method to achieve both the local and global tracking control based on a simplified dynamic model of WMR [9]. Lee et al. solved the tracking and regulation problems simultaneously using the backstepping method [10]. Considering the system uncertainties, the backstepping control was combined with SMC and adaptive compensation [11–13]. Focusing on that the SMC method has high robustness, the tracking control for a WMR was solved by the SMC method in [14–17]. Since the finite-time control algorithm features better performance than an asymptotically converged controller does, Ou et al. presented a finite-time approach to achieve tracking control in [18]. The twisting algorithm and terminal sliding mode (TSM) method were employed in [19,20]. In [21], A.S. Al-Araji et al. designed a feedforward controller using neural networks to find reference torques. Due to the universal approximation capability of the fuzzy control, it was introduced in [13,22] to enhance the performance of traditional controllers. And the visual servoing tracking controllers were developed in [23,24]. Although the artificial intelligent methods provide new ways for tracking control of a WMR, further studies of the nonlinear control methods are still valuable.

Previous studies theoretically achieve the control objective of tracking control and thus have great significance for the control of a WMR. On the other hand, there are some problems in the existing literatures. Firstly, since the control input in an actual control system is a motor torque, it is straightforward to use a dynamic

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model in the control system design [19,25]. Note that the dynamic model is ignored or simplified in [9,10,26,27]. So, the control laws are not directly applicable. Secondly, the linear SMC methods of [15–17] are about asymptotical convergence, which means that the convergence rate is at best exponential with infinite settling time. In addition, the switching gain of SMC methods is usually chosen a large value to guarantee the robustness of the closed-loop system. It results in large amplitude of the control input. Thirdly, the robustness of the finite-time control system of [18] is not studied. And the chattering problem of adaptive finite-time method of [19] is not solved, which should be considered with the boundary of adaptive gain simultaneously [28,29].

The main contribution of this study is that a robust and adaptive control scheme is presented using the finite-time algorithm of [30–32]. As the major technical breakthrough, a TSM disturbance observer and an adaptive compensator are designed for this algorithm. The disturbance observer could give a fast accurate compensation for the system uncertainties, which avoids the large conservative switching gain. Furthermore, in the case that the boundary information of system uncertainties is unknown, the adaptive compensator could enhance the robustness of the control system. Moreover, a solution is given for the chattering reduction, which simultaneously guarantees the boundedness of adaptive gain.

This paper employs a dynamic model of a WMR and takes the motor torque as the control input. First, the tracking control is transformed to the problem of finite-time stabilization of a double integral system. Then, the design of control system is divided into two parts: a tracking controller and a compensator. The former is responsible for the tracking control of a nominal plant, which is designed using the finite-time algorithm. The latter ensures the robustness of the control system against system uncertainties, which is composed by a TSM disturbance observer and an adaptive compensator. Meanwhile, the adaptive compensator is improved by using the boundary layer approach and switching adaptive law. As a result, the control system yields the ultimate boundedness of both the tracking error and adaptive gain.

The rest of this paper is organized as follows. Preliminaries are presented in Section 2. Section 3 shows the dynamic model of a WMR. The tracking problem is also transformed to the problem of stabilizing a double integral system. In Section 4, the main result of this study, the control system design, is presented. And the simulation results are shown in Section 5. Finally, some concluding remarks are given in Section 6.

2. Preliminaries

This section presents a review of the Lyapunov theorem for finite-time stability and some useful lemmas.

Theorem 1 ([30,33]). *Consider the following non-Lipschitz continuous autonomous system*

$$\dot{x} = f(x), \quad f(0) = 0, \ x \in R^n, \tag{1}$$

where $f : R^n \to R^n$ is locally Lipschitz continuous. Assume there is a C^1 function $V(x)$ defined on a neighborhood $D \subset R^n$ of the origin, such that:

(1) *$V(x)$ is positive definite;*
(2) *$\dot{V}(x) + \alpha V^{\eta}(x) \le 0, \ x \in D, \alpha > 0, \ \eta \in (0, 1)$.*

Then, System (1) is locally finite-time stable at the origin. If $D = R^n$ and $V(x)$ is also radially unbounded, then System (1) is globally finite-time stable at the origin. The settling time, which depends on the initial state $x(0) = x_0$, satisfies $T_x(x_0) \le \frac{V(x_0)^{1-\eta}}{\alpha(1-\eta)}$, for all x_0 in some open neighborhood of the origin.

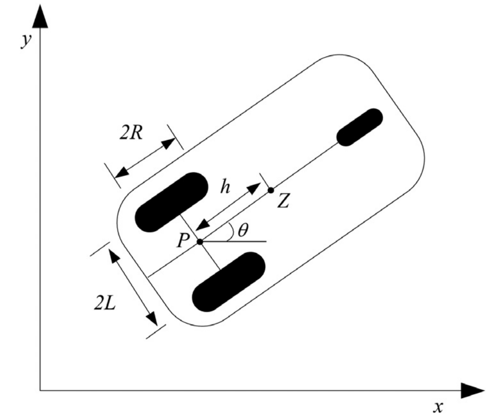

Fig. 1. Structure of WMR.

Moreover, an extended Lyapunov description of finite-time stability can be given with the form of fast TSM as

$$\dot{V}(x) + \kappa V(x) + \alpha V^{\eta}(x) \le 0, \quad \kappa > 0, \tag{2}$$

and the settling time satisfies $T \le \frac{1}{\kappa(1-\eta)} \ln \frac{\kappa V^{1-\eta}(x_0)+\alpha}{\alpha}$, where $V(x_0)$ is the initial value of $V(x)$.

Lemma 1 ([31]). *For any real numbers a_1, a_2, p_1, and p_2, if $p_1 > 0$ and $p_2 > 0$, then the following inequality holds*

$$|a_1|^{p_1} |a_2|^{p_2} \le \frac{p_1 |a_1|^{p_1+p_2}}{p_1 + p_2} + \frac{p_2 |a_2|^{p_1+p_2}}{p_1 + p_2}.$$

Lemma 2 ([32]). *For any real numbers a_3 and a_4, if $0 < p' = \frac{p_3}{p_4} < 1$, and p_3 and p_4 are positive odd integers, then*

$$\left| a_3^{p'} - a_4^{p'} \right| \le 2^{1-p'} |a_3 - a_4|^{p'}.$$

Lemma 3 ([32]). *For any real numbers c_i, $i = 1, 2, \ldots, n$ and $0 < j \le 1$, the following inequality holds*

$$(|c_1| + |c_2| + \cdots + |c_n|)^j \le |c_1|^j + |c_2|^j + \cdots + |c_n|^j.$$

3. Dynamic model of WMR

A WMR (Fig. 1) has one front castor wheel and two driving wheels. The castor wheel prevents the robot from tipping over as it moves on a plane. Two DC motors are the actuators of left and right wheels. Its dynamic equation and nonholonomic constraint are [16]

$$\begin{cases} M(\varphi)\ddot{\varphi} + C(\varphi, \dot{\varphi})\dot{\varphi} + G(\varphi) = B(\varphi)\tau + J^{\mathrm{T}}(\varphi)\lambda \\ J(\varphi)\dot{\varphi} = 0, \end{cases} \tag{3}$$

where φ denotes the pose vector, $M(\varphi)$ is a symmetric positive definite inertia matrix, $C(\varphi, \dot{\varphi})$ presents the vector of centripetal and Coriolis torques, $G(\varphi)$ is the gravitational torques, $B(\varphi)$ is the input transformation matrix, τ is the control torque, and λ is a Lagrange multiplier.

Assuming that the mobile robot moves in the horizontal plane, in this case, $G(\varphi)$ is equal to zero. The center of mass for mobile robot is located in the middle of axis connecting the rear wheels in P point as shown in Fig. 1, therefore, $C(\varphi, \dot{\varphi})$ is equal to zero [21].

Since $C(\varphi, \dot{\varphi}) = G(\varphi) = 0$, the system dynamic equation becomes

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} = \frac{1}{R} \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ L & -L \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} + \begin{bmatrix} \sin\theta \\ -\cos\theta \\ 0 \end{bmatrix} \lambda, \tag{4}$$