Neurocomputing 198 (2016) 74–79

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Disturbance observer-based robust control for trajectory tracking of wheeled mobile robots

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ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form
29 October 2015
Accepted 16 November 2015
Available online 10 March 2016

Keywords:
Adaptive tracking control
Disturbance observer
Wheeled mobile robot

ABSTRACT

This paper proposes an adaptive controller for the trajectory tracking of a nonholonomic wheeled mobile robot with nonholonomic constraints in the presence of external disturbances and unknown parameters. A new scheme is proposed to design an adaptive virtual velocity controller and torque control law. Meanwhile, a disturbance observer is applied to estimate the lumped disturbance to achieve the feedforward compensation. Simulation results demonstrate the effectiveness of the proposed control scheme.

1. Introduction

In the past few decades, research on wheeled mobile robot (WMR) has been widely investigated because of its extensive application in many fields such as industry, agriculture, service industry, national defense industry, etc. In early studies, only kinematic controllers for WMR were designed [1–3] based on the assumption that there are some kinds of dynamic controllers that can produce perfectly the same velocity. However, it is hard to design this kind of dynamic controllers. Therefore, some researchers changed the object from kinematic model to kinematic and dynamic model [4,5]. It should be pointed out that these proposed controllers are concerned with known parameters of the WMR. However, it is almost impossible to obtain the exact values of the parameters of the WMR in practice.

To address this problem, many methods such as adaptive and robust control have been proposed for the WMR with unknown parameters. In [6], an adaptive tracking controller has been presented for the WMR with unknown parameters using the backstepping approach. In [7], a robust adaptive controller has been applied to overcome uncertainties as well as the external disturbances. Then, the work [8] has introduced a novel adaptive controller, which uses a fuzzy logic system to esitmate the unknown robot parameters for the WMR, while the work [9] has dealt with the problem based on sliding mode control. Then, some researchers have focused on the implementation of the robot trajectory tracking, for example, how to observe the unmeasured velocities [10,11], deal with the input saturation [12], obtain the desired trajectory [13,14], detect the fault [15,16], and so on. In [10], a novel adaptive observer is developed to estimate the unmeasured velocities using transformation matrices. It can also deal with uncertain parameters and quadratic velocity terms for the WMR. The work [11] has proposed a new adaptive control scheme including a new adaptive state feedback controller and two high-gain observers to estimate the unknown velocities. Under the condition of external disturbances and input saturation [12] has proposed a tracking and stabilization scheme for WMR. The work [15] has presented a prediction error based fault detection algorithm to detect the faults in the dynamic model. Recently, the work [16] has proposed a nonlinear observer to detect the fault for the WMR. The work [17] has investigated an adaptive robust controller to deal with the trajectory tracking problem with parametric and nonparametric uncertainties in the WMR. The tracking problem for the WMR with kinematic and dynamic uncertainties has been addressed in [18]. A new nonlinear disturbance observer for robotic manipulators is derived in [19]. Based on disturbance observer based control techniques the work [20] has proposed a general framework for nonlinear systems with disturbances.

Motivated by [20,21], we design a disturbance observer to estimate the external disturbance and unknown parameters in the dynamic model, which can be treated as a lumped disturbance. Then, the disturbance observer will estimate the lumped disturbance. Compared with the adaptive robust control or sliding mode control, the proposed method will attenuate the disturbance and the influence of parameter variations by feedforward compensation. Which will reduce the burden of the controller in terms

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http://dx.doi.org/10.1016/j.neucom.2015.11.099

of large amplitude of disturbance. In the end, the analysis of the system stability is verified using Lyapunov approach.

2. Robot model and problem formulation

A two-wheeled robot is considered in Fig. 1. X is the moving direction of the WMR in $\{X, P_c, Y\}$, P_c is the mass center. P_o is the geometrical center. The distance between the two wheels is $2b$. r is the wheel's radius. d represents the distance between P_o and P_c, which is a unknown constant. The robot is in the fixed coordinate $\{x, o, y\}$ and the angle between axis X and axis x is θ.

The WMR's model is expressed as [4,8]

$$\dot{q} = S(q)\eta \tag{1}$$

$$M(q)\ddot{q} + C(q,\dot{q}) + F(\dot{q}) + \tau_d = B(q)\tau - A^T(q)\lambda \tag{2}$$

where $q = (x, y, \theta)^T$ denotes the position and orientation of the robot, $\eta = (\nu, \omega)^T$ is a vector of line and angular velocity, respectively. $\tau = (\tau_1, \tau_2)^T$ denotes the control torques of the WMR. λ is a constraint force. τ_d denotes the bounded unknown disturbances. $M(q)$ is a symmetric and positive-definite inertia matrix, $C(q,\dot{q})$ is the centripetal and coriolis matrix, $F(\dot{q})$ denotes the surface friction, $B(q)$ is the input transformation matrix. The mass of the WMR is m, inertia moment is J. Matrices $S(q), M(q), C(q,\dot{q}), B(q)$, and $A(q)$ are given as follows

$$S(q) = \begin{bmatrix} \cos\theta & -d\sin\theta \\ \sin\theta & d\cos\theta \\ 0 & 1 \end{bmatrix},$$

$$M(q) = \begin{bmatrix} m & 0 & md\sin\theta \\ 0 & m & -md\cos\theta \\ md\sin\theta & -md\cos\theta & J \end{bmatrix},$$

$$C(q,\dot{q}) = \left[md\dot{\theta}^2 \cos\theta md\dot{\theta}^2 \sin\theta 0 \right],$$

$$B(q) = \frac{1}{r}\begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ b & -b \end{bmatrix}, \quad A(q) = \begin{bmatrix} -\sin\theta \\ \cos\theta \\ -d \end{bmatrix}^T.$$

Remark 2.1. The friction term $F(\dot{q})$ satisfies $\|F(\dot{q})\| \le a_1 \|\dot{q}\| + a_2$ where a_1 and a_2 are positive constants.

The nonholonomic constraint implies that the mobile base satisfies the conditions of non slipping and pure rolling. Thus, the nonholonomic constraint is

$$A(q)\dot{q} = 0. \tag{3}$$

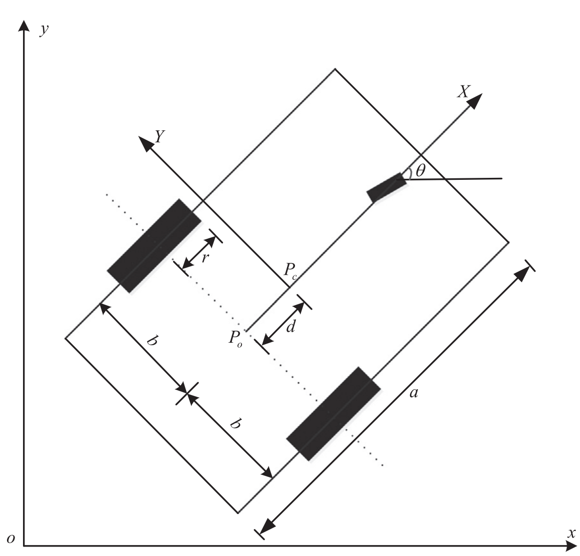

Fig. 1. A two-wheeled nonholonomic mobile robot.

From (1), one can obtain that

$$\ddot{q} = S(q)\dot{\eta} + \dot{S}(q)\eta. \tag{4}$$

Substituting (4) into (2), it yields

$$M(q)S(q)\dot{\eta} + M(q)\dot{S}(q)\eta + C(q,\dot{q}) + F(\dot{q}) + \tau_d = B(q)\tau - A^T(q)\lambda. \tag{5}$$

Multiplied by $S^T(q)$ on the left side of (5), one has

$$S^T(q)M(q)S(q)\dot{\eta} + S^T(q)M(q)\dot{S}(q)\eta + S^T(q)C(q,\dot{q}) + S^T(q)(F(\dot{q}) + \tau_d) = S^T(q)B(q)\tau - S^T(q)A^T(q)\lambda. \tag{6}$$

From the definitions of matrices $S(q), A(q), M(q), C(q,\dot{q})$, it can be seen that

$$S^T(q)A^T(q) = 0, S^T(q)M(q)\dot{S}(q)\eta + S^T(q)C(q,\dot{q}) = 0, \tag{7}$$

under which, (6) becomes

$$\overline{M}\dot{\eta} + \delta = \overline{B}\tau \tag{8}$$

where $\overline{M} = \begin{bmatrix} m & 0 \\ 0 & J - md^2 \end{bmatrix}$, $\delta = S^T(q)(F(\dot{q}) + \tau_d)$ and $\overline{B} = \frac{1}{r}\begin{bmatrix} 1 & 1 \\ b & -b \end{bmatrix}$.

Let $(x_r, y_r, \theta_r)^T$ represent the desired reference of the WMR, which is described by:

$$\begin{cases} \dot{x}_r = \nu_r \cos\theta_r - d\omega_r \sin\theta_r \\ \dot{y}_r = \nu_r \sin\theta_r + d\omega_r \cos\theta_r \\ \dot{\theta}_r = \omega_r \end{cases} \tag{9}$$

where ν_r and ω_r denote the desired linear and angular velocities of the robot.

The purpose is to design torque controller τ for the WMR to make the real trajectory track the desired one. To achieve this objective, some assumptions are listed.

Assumption 2.1. The disturbance δ and its derivative are both bounded. In addition, δ has a constant value in steady state, i.e., $\lim_{t\to+\infty} \|\dot{\delta}\| = 0$.

Assumption 2.2. The reference linear and angular velocities ν_r, ω_r and their first-order derivatives $\dot{\nu}_r$, $\dot{\omega}_r$ are bounded.

Assumption 2.3. The unknown parameters of the WMR are in known compact sets.

Remark 2.2. Since the WMR is a large inertia system, it is insensitive to the fast time-varying disturbance. Thus, it is reasonable to suppose that $\lim_{t\to+\infty} \|\dot{\delta}\| = 0$. In actual case, the velocity and acceleration of the wheeled mobile robot are always limited by the motors. Moreover, the parameters m, J and d of the mobile robot cannot be obtained accurately. But the range of the parameters can be estimated. Therefore, it is reasonable to assume that the unknown parameters of the mobile robot are in known compact sets.

3. An adaptive controller and disturbance observer design

In this part, a novel scheme including parameter estimators and control laws is proposed. Based on the kinematic model (1), a virtual control (ν_c, ω_c) will be designed to provide the virtual linear and angular velocity. Then, the torque controller τ is designed to generate real linear and angular velocities to track the virtual one. The disturbance observer is applied to estimate the lumped disturbance to achieve the feedforward compensation. The block diagram of the closed-loop system is shown in Fig. 2.