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Research article

Adaptive nonsingular fast terminal sliding-mode control for the tracking problem of uncertain dynamical systems

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ABSTRACT

In this paper, robust and adaptive nonsingular fast terminal sliding-mode (NFTSM) control schemes for the trajectory tracking problem are proposed with known or unknown upper bound of the system uncertainty and external disturbances. The developed controllers take the advantage of the NFTSM theory to ensure fast convergence rate, singularity avoidance, and robustness against uncertainties and external disturbances. First, a robust NFTSM controller is proposed which guarantees that sliding surface and equilibrium point can be reached in a short finite-time from any initial state. Then, in order to cope with the unknown upper bound of the system uncertainty which may be occurring in practical applications, a new adaptive NFTSM algorithm is developed. One feature of the proposed control law is their adaptation techniques where the prior knowledge of parameters uncertainty and disturbances is not needed. However, the adaptive tuning law can estimate the upper bound of these uncertainties using only position and velocity measurements. Moreover, the proposed controller eliminates the chattering effect without losing the robustness property and the precision. Stability analysis is performed using the Lyapunov stability theory, and simulation studies are conducted to verify the effectiveness of the developed control schemes.

1. Introduction

Nonlinear dynamical systems suffer from the performance degradation caused by uncertainties and external disturbances. Many nonlinear control schemes have been proposed to improve the control performance of these perturbed systems such as feedback linearization control [1–3], Backstepping control [4–6], optimal control [7–9], intelligent control [10–12], and sliding-mode control [13–40]. It is well-known that the sliding-mode control is an important control procedure which has many attractive features such as good transient performance, robustness to parameter variations and insensitivity to disturbances. The basic idea of the sliding-mode control is to drive and maintain the system trajectory on a sliding surface designed a priori in the state space. In conventional linear sliding-mode (LSM) control, linear hyperplane is used as the sliding surfaces [13–18]. However, LSM control ensures asymptotic convergence of the system states to the equilibrium point, but not in finite-time. To achieve the finite-time convergence and enhance the convergence properties of dynamical systems, terminal sliding-mode (TSM) control and fast terminal sliding-mode (FTSM) control which adopts nonlinear sliding surfaces is developed [19–25]. Compared to the TSM, the FTSM has faster convergence speed when the states are far from the origin.

However, these control methods suffer from the singularity problem because the terms with negative fractional powers may exist. To overcome this problem, a new type of sliding-mode control techniques called nonsingular terminal sliding-mode (NTSM) and nonsingular fast terminal sliding-mode (NFTSM) are recently developed [26–36]. Compared to other sliding-mode manifolds, the NFTSM control has finite-time convergence, fast speed when the states are far from the origin, singularity avoidance and chattering reduction. Thanks to such promising features, NFTSM has become increasingly popular for high-precision control in different engineering sectors like space exploration [42,43], underwater navigation [44,45], machines with multiple motion axes [46], sophisticated industrial robotic applications such as welding [47], painting [48], and object grasping [49], etc.

Many researchers have investigated the tracking control

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Abbreviations

LSM	Linear Sliding-Mode
TSM	Terminal Sliding-Mode
FTSM	Fast Terminal Sliding-Mode
NTSM	Nonsingular Terminal Sliding-Mode
NFTSM	Nonsingular Fast Terminal Sliding-Mode
RNFTSMC	Robust Nonsingular Fast Terminal Sliding-Mode Control
ANFTSMC	Adaptive Nonsingular Fast Terminal Sliding-Mode Control

problem for uncertain nonlinear systems using TSM control and NTSM control. In Ref. [26], a global NTSM control for rigid manipulators is developed to ensure the elimination of the singularity problem associated with the conventional TSM control. In Ref. [27], a continuous finite-time control scheme for rigid robotic manipulators is proposed using a NFTSM control. The robustness of the controller is established using the Lyapunov stability theory. Fast and high-precision tracking performance is obtained compared with the conventional TSM method. In Ref. [28], a fast nonsingular integral terminal sliding-mode control designed by introducing power integral terms which contain a boundary-like structure. The proposed controller can avoid the singularity problem without any constraint and provide faster responses. In Ref. [29], an NFTSM control which is able to avoid the possible singularity during the control phase is adopted in the robust high-precision control of uncertain nonlinear systems. In Ref. [30], an NTSM control for nonlinear systems is developed and it is shown that the proposed control strategy can eliminate the singularity while guaranteeing the finite-time reachability of the system. However, all of the above-mentioned work assumes the prior knowledge of upper bound of the system uncertainty. Unfortunately, the upper bound may not be easily obtained in practical applications due to the complexity of the structure of uncertainties. Therefore, many kinds of controllers which combine the structure of SMC and adaptive control have been proposed to overcome the problem associated with the unknown bounds. In Ref. [31], a robust adaptive TSM control is developed for n-link rigid robotic manipulators with uncertain dynamics. An adaptive mechanism is introduced to estimate the unknown parameters of the upper bounds of the system uncertainties in the sense of Lyapunov. In Ref. [32], an adaptive global FTSM control is proposed for the tracking control of micro-electro-mechanical systems vibratory gyroscopes under unknown model uncertainties and external disturbances. The proposed controller can estimate the unknown upper bound. In Ref. [33], an adaptive second-order TSM controller for robotic manipulators is proposed to deal with the system uncertainties whose upper bounds are not required to be known in advance. The time derivative of the control input is used in the controller to eliminate chattering phenomenon. The idea of using the time derivative of the control signal to have a smooth control input is also investigated in Ref. [34] and the designed adaptive gain-tuning control law removes the necessity of gaining information about the upper bounds of the external disturbances. In Ref. [35], a robust adaptive sliding-mode controller is proposed for a class of uncertain nonlinear multi-input multi-output systems. The upper bounds of the uncertainties are not needed in the procedure for the controller design, and the controller is continuous, which guarantees that the tracking error can converge to a small residual set. In Ref. [36], a robust adaptive TSM control is proposed to estimate the upper bounds of the system uncertainty where only position and velocity measurements are available. It is also proved that the system uncertainty is related not only to the model properties, but also to the controller structure. In Ref. [37], a robust adaptive TSM control for tracking problems in robotic manipulators. By applying this adaptive controller, it is possible to estimate the upper bound of uncertainties and disturbances.

It is worth noting that all the above works mainly focused on the adaptive estimation of the upper bounds of the uncertainties using TSM control and FTSM control but neither of them have considered NFTSM control. It is well known that the main advantage of using NFTSM control is singularity avoidance, fast speed when the states are far from the origin, and strong robustness with respect to system uncertainty and external disturbances. To the best of our knowledge, not many works provide adaptive NFTSM control.

The novelty of the approach presented here can be understood by considering the following points: (1) Unlike the existing robust TSM approaches [26–30] which are formulated under the assumption that the bound of the system uncertainty and disturbances are usually required to be known in advance, an adaptive parameter-tuning procedure is proposed here to estimate the unknown upper bounds. Therefore, the bound of the lumped uncertainty is unnecessary. (2) Compared with the existing adaptive TSM control [31–37] which cannot guarantee singularity avoidance, the novel adaptive control law does not exhibit any singularity problem. Furthermore, the convergence rate of the system state is improved when the system state is far away from the equilibrium. (3) Unlike [33,34] where the acceleration signal is needed for the control design, the proposed approaches need only position and velocity information, which can be easily obtained using appropriate sensors. (4) By employing the proposed controllers, the position and the velocity tracking errors can be stabilized to zero in a short finite-time simultaneously. Also, the chattering effect is eliminated without losing the robustness property and the precision.

The remainder of this paper is organized as follows: In Section 2, the problem statement and some preliminaries are given. The design procedures of the proposed NFTSM control and stability analysis are derived in Section 3. In Section 4, we extend the NFTSM methods to n-degree-of freedom robotic manipulators. The numerical simulation results are included in Section 5. Finally, the work is concluded in Section 6.

2. Problem statement and preliminaries

2.1. Problem statement

Consider the following second-order uncertain nonlinear dynamical system

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x) + \Delta f(x) + d(t) + b(x)\tau(t) \\ y &= x_1 \end{aligned} \tag{1}$$

where x_1 and x_2 are the state variables of the system, y is the output signal, both $f(x)$ and $b(x)\neq 0$ are smooth nonlinear functions in terms of x, $\Delta f(x)$ denotes the system uncertainty, $d(t)$ denotes the external disturbances and $\tau(t)$ is the control input.

Let define the tracking error $e_1 = y - y_d$ and its derivative $e_2 = \dot{y} - \dot{y}_d$ where y_d is the reference signal. Then, the error dynamic of the system can be written as

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= F(x) + D(x,t) + B(x)\tau(t) \end{aligned} \tag{2}$$

where $F(x) = f(x) - \ddot{y}_d$, $B(x) = b(x)$ and $D(x,t) = \Delta f(x) + d(t)$ is