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Finite-time synchronization control for bilateral teleoperation under communication delays

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ABSTRACT

This paper presents a new adaptive fast terminal sliding mode tracking control scheme for nonlinear teleoperation system. With the use of the terminal sliding mode technique, the faster and high-precision synchronization performances between the master and the slave are achieved. In the absence of the knowledge for the system uncertainties, an adaptive sliding mode controller is presented. A robust term is employed to compensate the adaptive estimation error. The tracking errors converge to zero in finite time with the new controller. Finally, simulations are presented to show the effectiveness of the proposed approach.

1. Introduction

A teleoperation system can extend the human-sensing and manipulative capabilities to the remote environment. Now the teleoperation system has been widely used in many areas, for instance space operation, robotic surgery, handling of radiate and harmful materials and underwater exploration [1].

The sliding mode control (SMC) is a powerful theory for controlling uncertain systems, and the main advantage is that the controlled system with sliding mode exhibits robustness properties with respect to both internal parameter uncertainties and external disturbance. Generally speaking, the SMC technique consists of two steps: (i) choose a stable manifold as the sliding mode and (ii) design a proper controller driving the system to the sliding surface. The SMC has been embraced many applications in teleoperation field [2–4]. However, the sliding mode used in above papers are all linear sliding mode, i.e., the system state variables slide to the equilibrium point exponentially on the sliding surface. Although the convergence rate may be arbitrarily fast from adjusting appropriate parameters, stabilizing dynamical systems cannot be achieved in finite time. Accomplishing finite-time error convergence is more desirable in practice, because of the practical applications of teleoperation. To get a finite-time convergence performance, the terminal sliding mode control (TSMC) with a nonlinear sliding hyperplane was first proposed in [5]. Successively, the TSMC has been developed in many literatures [6–9]. Compared with the linear hyperplane-based modes, the TSM offers some superior properties such as fast, finite time convergence. However, the existing TSM controller design methods still have a singularity problem. To tackle this problem, [10] proposed a new global non-singular terminal sliding mode controller. Then in [11], a new continuous finite-time control scheme for rigid robotic manipulator was presented by using a nonsingular terminal sliding mode (NTSM). To deal with the uncertainties existing in the system, an adaptive terminal sliding mode controller was proposed in [12] for robotic manipulators. Then, a MIMO adaptive fuzzy terminal sliding mode controller for robotic manipulators was presented in [13]. However, the terminal sliding mode used in [12] and [13] had same defect on dealing with the singularity problem. A new controller combining a continuous nonsingular TSMC with an adaptive learning algorithm and fuzzy logic system was proposed in [14]. With the new controller, the closed-loop stability and the finite-time convergence of tracking errors could be guaranteed. Considering the chattering problem, [15] combined the synergetic control and the TSMC, the proposed control scheme had the characteristics of finite time convergence and the chattering free phenomenon. However, it is necessary to note that, the TSM used in [10–15]have a slow convergence speed when the initial system state is far away from the equilibrium. [16] proposed a fast terminal sliding mode (FTSM) concept, which ensured fast transient convergence both at a distance from and at a close range of the equilibrium. In [17], a new nonsingular fast terminal sliding mode (NFTSM) that embraced a faster convergence rate and nonsingular performance was presented.

Even though the finite-time control method has been widely used in controlling the robotic system and the spacecraft [18–21]. To our best knowledge, there is almost no result reported for teleoperation system design. It should be noted that the method

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proposed for controlling one manipulator could not be directly used for the teleoperation design because two interconnected manipulators are enclosed. In teleoperation system, the influence from the human operator and the external environment should be considered. The models of human operator and environment had been considered in [22–26] to improve the force tracking performance. Moreover, in bilateral teleoperation system, the master and the slave are connected via a long communication network, then the time delay cannot be ignored. In recent years, many methods were proposed to deal with the time-delay problem. A proportional derivative plus damping (PD+d) controller was proposed in [27]. A simple proportional plus damping (P+d) controller was proposed in [28]. For time-varying delays, [29,30] proposed a simple P+d controller and a direct force feedback (DFF) controller.

In this paper, a NFTSM based finite time control scheme is proposed for the teleoperation system under constant time delay. The adaptive technique is used to estimate the bound of system uncertainties. The master and slave controllers are designed based on the nonsingular fast terminal sliding mode method. Based on the Lyapunov stability theory, we show that the system tracking errors converge to zero in finite time. Finally, simulations are performed to show the effectiveness of the proposed method.

This paper is organized as follows. Section 2 presents some preliminary knowledge for the models of master, slave, human operator and external environment. In Section 3, the adaptive finite time control scheme is given. In Section 4, the performance analysis process is presented. Additionally, the simulation results are also shown in Section 4. Finally, Section 5 concludes with a summary of the obtained results.

2. Problem formulation

2.1. Dynamics of master and slave

The Euler–Lagrange equations of motion for n-link master and slave manipulators are given as

$$\begin{cases} M_{q_m}(q_m)\ddot{q}_m + C_{q_m}(q_m,\dot{q}_m)\dot{q}_m + G_{q_m}(q_m) + B_m(\dot{q}_m) = \tau_m + J_m^T(q_m)F_h \\ M_{q_s}(q_s)\ddot{q}_s + C_{q_s}(q_s,\dot{q}_s)\dot{q}_s + G_{q_s}(q_s) + B_s(\dot{q}_s) = \tau_s - J_s^T(q_s)F_e \end{cases} \tag{1}$$

where $i=m/s$ stands for the master and the slave manipulator, respectively; $q_i(t) \in \mathbb{R}^n$ is the vector of the joint displacement; $\dot{q}_i(t) \in \mathbb{R}^n$ is the vector of joint velocity; $\ddot{q}_i(t) \in \mathbb{R}^n$ is the vector of joint acceleration; $M_{q_i}(q_i): \mathbb{R}^n \to \mathbb{R}^{n\times n}$ is the positive-definite inertia matrix; $C_{q_i}(q_i,\dot{q}_i): \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^{n\times n}$ is the matrix of centripetal and coriolis torques; $G_{q_i}(q_i): \mathbb{R}^n \to \mathbb{R}^n$ is the gravitational torque; $B_i(\dot{q}_i) \in \mathbb{R}^n$ is the bounded external disturbances i.e., $\|B_i(\dot{q}_i)\| \le \overline{B}_i$; $J_i(q_i) \in \mathbb{R}^{n\times n}$ is the Jacobian matrix; F_h, $F_e \in \mathbb{R}^n$ are the human-operator force and the environment force, respectively; $\tau_i \in \mathbb{R}^n$ is the applied torque.

Property 1. *The inertia matrix $M(q)$ is a symmetric positive-definite function, and there exist positive constants m_1 and m_2 such that $m_1 I \le M(q) \le m_2 I$. I is an identity matrix with the corresponding dimension.*

Property 2. *For all $q, x, y \in \mathbb{R}^{n\times 1}$, there exists a positive scalar a_i such that $\|C(q,x)y\| \le a_i \|x\|\,\|y\|$.*

Property 3. *There exists positive scalar μ_G such that $\|G(q)\| \le \mu_G$.*

Property 4. *There exists positive scalar μ_J such that $\|J(q)\| \le \mu_J$.*

Throughout this paper, unless otherwise stated, by a vector norm, the vector 2-norm is meant and a matrix norm, the induced matrix 2-norm is meant.

2.2. Kinematics of master and slave

The generalized end-effector positions x_m and x_s of the master and the slave can be expressed as

$$x_m = h_m(q_m), \quad x_s = h_s(q_s) \tag{2}$$

where $h_m(q_m)$ and $h_s(q_s)$ are nonlinear transformation describing the relation between the joint-space and task-space positions. The Jacobian-based relationships between the task-space and the joint-space velocities are

$$\dot{x}_m = J_m(q_m)\dot{q}_m, \dot{x}_s = J_s(q_s)\dot{q}_s \tag{3}$$

where $J_m(q_m)$ and $J_s(q_s)$ are obtained basing on $h_m(q_m)$ and $h_s(q_s)$ directly.

Differentiating the above functions with respect time, yields

$$\begin{aligned} \ddot{x}_m &= \dot{J}_m(q_m)\dot{q}_m + J_m(q_m)\ddot{q}_m \\ \ddot{x}_s &= \dot{J}_s(q_s)\dot{q}_s + J_s(q_s)\ddot{q}_s \end{aligned} \tag{4}$$

2.3. System model with operator and environment

The dynamics of the human operator and the environment are naturally specified in the task space as it is the space in which they make contact with the master and the slave manipulators. The models used in some classic literatures [22–26] are given as follows:

$$\begin{aligned} F_h &= f_h - M_h\ddot{x}_m - B_h\dot{x}_m - K_h(x_m - x_{m0}) \\ F_e &= f_e + M_e\ddot{x}_S + B_e\dot{x}_s + K_e(x_s - x_{s0}) \end{aligned} \tag{5}$$

where M_h, M_e, B_h, B_e, K_h and K_e are constant, symmetric and positive-definite matrices corresponding to the human operator and external environment mass, damping and stiffness. Moreover, f_h stands for the human exogenous force and f_e represents the environment exogenous force. $x_{s\ 0}$ and $x_{m\ 0}$ represent the contact points of the environment and the hand of the human operator.

Combining the human operator and the environment models to the master and the slave models and transforming the dynamics of the operator and the environment from the task-space to the joint-space, we have

$$F_h = f_h - M_h(\dot{J}_m(q_m)\dot{q}_m + J_m(q_m)\ddot{q}_m) - B_hJ_m(q_m)\dot{q}_m - K_h(h_m(q_m) - x_{m0})$$

$$F_e = f_e + M_e(\dot{J}_s(q_s)\dot{q}_s + J_s(q_s)\ddot{q}_s) + B_eJ_s(q_s)\dot{q}_s + K_e(h_s(q_s) - x_{s0}) \tag{6}$$

So with the dynamics of the master and the slave (1), we have

$$\begin{cases} M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + G_m(q_m) + B_m(\dot{q}_m) = \tau_m \\ M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G_s(q_s) + B_s(\dot{q}_s) = \tau_s \end{cases} \tag{7}$$

where

$$\begin{aligned} M_m(q_m) &= M_{q_m}(q_m) + J_m^T(q_m)M_hJ_m(q_m) \\ C_m(q_m,\dot{q}_m) &= C_{q_m}(q_m,\dot{q}_m) + J_m^T(q_m)B_hJ_m(q_m) + J_m^T(q_m)M_h\dot{J}_m(q_m) \\ G_m(q_m) &= G_{q_m}(q_m) + J_m^T(q_m)K_h(h_m(q_m) - x_{m0}) - J_m^T(q_m)f_h \\ M_e(q_e) &= M_{q_s}(q_s) + J_s^T(q_s)M_eJ_s(q_s) \\ C_s(q_s,\dot{q}_s) &= C_{q_s}(q_s,\dot{q}_s) + J_s^T(q_s)B_eJ_s(q_s) + J_s^T(q_s)M_e\dot{J}_s(q_s) \\ G_s(q_s) &= G_{q_s}(q_s) + J_s^T(q_s)K_e(h_s(q_s) - x_{s0}) + J_s^T(q_s)f_e \end{aligned} \tag{8}$$

In reality, similar to many engineering applications, it is impossible or very difficult to obtain an exact dynamic model of the master or the slave manipulators, due to the presence of large flexibility, Coulomb friction, backlash, unknown disturbance and so on. So we have $M_i(q_i) = M_{oi}(q_i) + \Delta M_i(q_i)$; $C_i(q_i,\dot{q}_i) = C_{oi}(q_i,\dot{q}_i) + \Delta C_i(q_i,\dot{q}_i)$; $G_i(q_i) = G_{oi}(q_i) + \Delta G_i(q_i)$; here $M_{oi}(q_i)$, $C_{oi}(q_i,\dot{q}_i)$ and $G_{oi}(q_i)$ are the nominal parts, whereas $\Delta M_i(q_i)$, $\Delta C_i(q_i,\dot{q}_i)$ and $\Delta G_i(q_i)$ represent the uncertain parts in system