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Finite-time output-feedback synchronization control for bilateral teleoperation system via neural networks

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ABSTRACT

The finite-time control problem is considered for bilateral teleoperation system via output feedback approach. A new observer is designed for the velocity estimation and the resulting velocity error system is proved to be semi-globally stable. The observer based output feedback finite-time controller is developed by employing a novel nonsingular fast integral terminal sliding mode. The closed-loop system is proved to be stable based on Lyapunov stability theory. It is shown that the master-slave synchronization error converges to zero in finite time. The merit of the proposed method is that the designed controller only uses the position information which renders that the master-slave synchronization error reaches zero in the prescribed time. Simulation and experiment are performed and the results demonstrate the effectiveness of the proposed method.

1. Introduction

Teleoperation systems have been developed to allow human operators to execute tasks in remote or hazardous environments, with a variety of applications ranging from space to underwater, nuclear plants, and so on. A teleoperation system is composed of human operator, master robot, communication channel, slave robot and remote environment [12]. If only the master motion and/or force are transmitted to the slave site, the teleoperation system is called unilateral. If there also exist the motion and/or force information transmissions from the slave site to the master site, the teleoperation system is called bilateral. The design of bilateral teleoperation is a challenging issue of control technology (see [12] and the references therein). A number of control approaches have been proposed, such as scattering method [1], wave variables [32], PD+d control [5], P+d control [13,17,30], adaptive control [21]. However, only asymptotic synchronization performance is provided with above control approaches, that is, the synchronization error between the master and the slave converges to zero when $t \to \infty$. One knows that the finite-time synchronization is expected for a teleoperation system for that the synchronization error converges to zero in a finite time. Therefore, it is significant to consider the finite-time control problem for the networked teleoperation system.

It is well known that terminal sliding mode (TSM) provides finite-time stability [27]. Similar with the linear sliding mode (LSM) technique, strong robustness with respect to uncertain dynamics can be obtained by using TSM [9,10,36]. Moreover, the state variables converge to zero in finite time. Generally, there exist singularity problem in TSM control which leads to the unboundedness of the control input [10]. To deal with the singularity problem, two kinds of methods have been

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proposed: directed method (designing nonsingular TSM) [10,29,33] and indirected method (switching between the LSM and the TSM) [11,28,31]. For the direct method, the zero velocity state will decelerate and complicate the reaching phase even though they are not attractors. For the indirect method, the settling time will be longer and the switching time from the LSM to TSM can not be achieved exactly. To solve above problems, integral terminal sliding mode (ITSM) surface was proposed and used in [4,18,20]. Then the singularity issue in TSM control does not exist any more for the reason that the negative fractional power is produced with the ITSM. In above literatures, the system convergence speed will be seriously limited when the initial state is far away from the equilibrium point. To solve this problem, a new NFITSM is developed by adding high-degree terms to provide the accelerated convergence speed. Moreover, the homogeneity in the bi-limit is employed to determine the degrees [19,22].

One knows that it is difficult to obtain the precise value of velocity in teleoperation system. The high-gain velocity observer [14] and the Immersion & Invariance (I&I) velocity observer [23] were introduced for teleoperation system to estimate the velocity signals. To provide the faster velocity estimation rate and higher estimation precision, the finite-time velocity observer was proposed, see [26,35] and the references cited therein. The sliding mode based finite-time velocity observers were developed for general mechanical system [6] and teleoperation system [7,16]. Nevertheless, similar with the general TSM control, the observation ability will be limited when the initial value of estimation error is larger, which will seriously prohibits their practical applications. What's worse, the system uncertainties are not adequately considered in the above cited literatures. The objective of this paper is to design a new neural networks (NNs) based FTSM finite-time velocity observer for the bilateral teleoperation system with uncertainties. To the best knowledge of the authors, the problem of finite-time synchronization control has not been well explored for networked teleoperation system via output feedback approach, which finally motivates this study.

In this paper, the finite-time output-feedback synchronization control problem is addressed for bilateral teleoperation system. The main contribution of this work is shown as follows. (i) A new neural network based FTSM finite-time velocity observer is designed in the presence of system uncertainties. Compared with the existing velocity observers, faster estimation rate and higher estimation precision can be achieved with the new observer. (ii) A novel NFITSM surface is developed without any switching operation and corresponding finite-time control algorithm is proposed to guarantee the finite-time synchronization between the master and the slave.

The remainder of the paper is organized as follows. Section 2 presents some preliminary knowledge for the dynamics of teleoperation system with the related properties and the knowledge of Radial Basis Function (RBF) NNs. New FTSM velocity observer is shown in Section 3. In Section 4, a new finite-time control algorithm for the teleoperator is presented. The simulation and experiment results are presented in Section 5. Finally, Section 6 concludes with a summary of the obtained results.

2. Preliminary

Consider a teleoperation system described by the following model

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m,\dot{q}_m)\dot{q}_m + G_m(q_m) &= \tau_m + F_h + \bar{Q}_m(q_m,\dot{q}_m) \\ M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + G_s(q_s) &= \tau_s + F_e + \bar{Q}_s(q_s,\dot{q}_s) \end{aligned} \tag{1}$$

where subscript m, s represent the master and the slave, respectively; $q_m(t)$, $q_s(t) \in \mathbb{R}^n$ denote the vectors of joint displacements; $\dot{q}_m(t)$, $\dot{q}_s(t) \in \mathbb{R}^n$ are the vectors of joint velocities; $\ddot{q}_m(t)$, $\ddot{q}_s(t) \in \mathbb{R}^n$ represent the vectors of joint accelerations; $M_m(q_m)$, $M_s(q_s) \in \mathbb{R}^{n\times n}$ are the positive definite inertia matrices; $C_m(q_m,\dot{q}_m)$, $C_s(q_s,\dot{q}_s) \in \mathbb{R}^{n\times n}$ denote the matrices of centripetal and coriolis terms; $G_m(q_m)$, $G_s(q_s) \in \mathbb{R}^n$ are the vectors of gravitational torques; $\bar{Q}_m(q_m,\dot{q}_m)$ and $\bar{Q}_s(q_s,\dot{q}_s)$ represent the unknown lumped uncertainties such as system model uncertainties, friction forces and external disturbances; F_h, $F_e \in \mathbb{R}^n$ are the torques applied by the human operator and the remote environment, respectively; τ_m, $\tau_s \in \mathbb{R}^n$ represent the applied control torques.

In this paper, the functions $M_i(q_i)$, $C_i(q_i,\dot{q}_i)$ and $G_i(q_i)$ are assumed to be known functions. In addition, following [26] we also assume that the nonlinear function $C_i(q_i,\dot{q}_i)\dot{q}_i$ is Lipschitz ($i = m, s$). The properties for robotic systems are revisited as follows [5,13,17,21,30]:

Property 1. *The matrix $M_i(q_i)$ is symmetric positive definite and bounded, i.e.,*

$$\lambda_{\min}(M_i(q_i))I \le M_i(q_i) \le \lambda_{\max}(M_i(q_i))I \tag{2}$$

where $\lambda_{\min}(M_i(q_i))$ and $\lambda_{\max}(M_i(q_i))$ denote the minimum and maximum eigenvalues of $M_i(q_i)$, I is an identity matrix.

Property 2. *The matrix $\dot{M}_i(q_i) - 2C_i(q_i,\dot{q}_i)$ is skew-symmetric.*

Property 3. *For all q_i, x, $y \in \mathbb{R}^n$, there exists a positive scalar c_i such that*

$$\|C_i(q_i,x)y\| \le c_i\|x\|\,\|y\| \tag{3}$$

where $\|\cdot\|$ denotes the Euclidean norm of a vector and the corresponding induced matrix norm.

For finite time control, the following definition and lemmas are needed.