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Research paper

A new continuous fractional-order nonsingular terminal sliding mode control for cable-driven manipulators☆

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A B S T R A C T

To ensure satisfactory control performance for the cable-driven manipulators under complex lumped uncertainties, a new continuous fractional-order nonsingular terminal sliding mode (CFONTSM) control scheme based on time delay estimation (TDE) is proposed and studied in this paper. The proposed control scheme contains three elements, a TDE element adopted to suitably cancel out the unknown lumped dynamics with purposely time-delayed signals of the closed-loop control system, a newly proposed FONTSM manifold adopted to realize finite-time convergence in the sliding mode phase and a fast-TSM-type reaching law adopted to ensure finite-time convergence in the reaching phase. The proposed control scheme is model-free and no longer needs system dynamics benefiting from TDE, which is very suitable and easy to use in practical applications. Meanwhile, high precision, fast convergence and good robustness against lumped uncertainties are ensured thanks to the newly proposed FONTSM manifold and adopted fast-TSM-type reaching law. Integrated stability analysis of the closed-loop control system is presented based on Lyapunov stability theory. Finally, the effectiveness of our proposed control scheme is demonstrated by comparative 2-DoFs (degrees-of-freedom) simulation and experiments.

1. Introduction

In the recent decades, conventional industrial robot manipulators have been broadly adopted in lots of practical applications thanks to their good capability for automatic jobs [1–3]. However, large moving mass and low flexibility will result in relative poor safety for physical human-robot interaction and more energy consumption. To effectively solve these issues, the cable-driven manipulators were designed and investigated [4–6]. By moving the drive units from joints to base and using cable-driven units to transmit force and motion, such cable-driven systems have much smaller moving mass, better flexibility and satisfactory safety [7–10]. Benefiting from all these superiorities, cable-driven manipulators are gradually turning into a fascinating research area [11–13].

However, control scheme development for cable-driven manipulators is much more difficult than that of traditional robot manipulators due to optimize the composition the joint flexibility and complex system dynamics. Thus, many scholars and engineers have devoted themselves to seek proper control schemes for such systems with flexible joints. Some robust and intelligent control schemes have been presented, such as sliding mode (SM) control [14], adaptive control [15], iterative learning control [16] and neural network control [17]. Usually, system dynamic model or complex approximation algorithm is required to apply above-mentioned methods, which, however, are not fit for real situations of cable-driven manipulators.

Time delay estimation (TDE) technique can be a simple but strongly efficient method to settle this problem. The central thought of TDE is to estimate and compensate the unknown lumped system dynamics just using its own time-delayed signals [18–23]. Benefiting from above mentioned mechanism, TDE technique can successfully get rid of the requirement of system dynamics and achieve the inspiring model-free nature in a simple way, which is very suitable and easy to use in complex real situations. Therefore, TDE has been broadly adopted in lots of systems since it was proposed [24–28]. Usually, TDE is used as the framework to enjoy the model-free feature, while other robust control methods, such as SM control and terminal SM (TSM) control, are used to guarantee satisfactory control performance under complex lumped disturbance. Exciting theoretical and experimental results have been achieved with TDE-based SM and TSM control schemes for robot manipulators [29–32], underwater robots [33–38], multiple DoFs robot

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cCub [39] and shape memory alloy actuator systems [25,40] . Nevertheless, most of above-mentioned works are restricted within integer-order (IO) control schemes and only IO calculus is adopted.

Fractional-order (FO) controllers using FO calculus have been broadly verified to be more effective than their IO counterparts for both IO and FO systems under complex lumped disturbance [41,42]. Thus, FO controllers have been widely applied for numerous systems, such as fractional chaotic system [43], robot manipulators [44,45], quadrotor UAV [46] and DC–DC buck converter [47]. Recently, TDE-based continuous FO nonsingular TSM (CFONTSM) control scheme had been proposed and investigated for robot manipulators [48]. The resulting control scheme merges TDE together with FONTSM and can enjoy the advantages from both sides while naturally overcome their limitations. Although exciting theoretical and experimental results had been reported, they can still be further promoted. The FONTSM manifold presented in [48] may result in relative poor dynamic performance during the sliding mode phase due to the FO integral element, which in turn may greatly affect the overall control performance.

In this paper, above issues are properly settled. A novel robust control scheme is proposed and investigated for the cable-driven manipulators. The proposed control scheme mainly contains three elements, a TDE element and a newly proposed FONTSM manifold element and a fast-TSM-type reaching law element. The TDE element is applied to form the basic structure and leads to a model-free frame for the overall control scheme. The newly proposed FONTSM manifold with an extra FO differential element can ensure better dynamic performance in the sliding mode phase than that of the existing FONTSM, while the fast-TSM-type reaching law can provide with satisfactory performance in the reaching phase and also ensure a continuous feature. Therefore, the newly designed control scheme is model-free and fit for real situations thanks to TDE. Meanwhile, it still has the capability to guarantee satisfactory control performance under complex lumped disturbance benefitting from the newly proposed FONTSM manifold and fast-TSM-type reaching law. Integrated stability analysis is presented based on Lyapunov stability theory. Finally, 2-DoFs (degrees-of-freedom) simulation and experimental verifications effectively demonstrate the superiorities of our newly proposed control scheme over the existing ones.

The primary contributions we seek to make are:

1) Propose a new FONTSM manifold. By introducing an extra FO differential element into the existing one, better control performance can be achieved;
2) Propose a new TDE-based CFONTSM control scheme combining the newly proposed FONTSM manifold with TDE technique and fast-TSM-type reaching law;
3) Give the integrated stability analysis using Lyapunov stability theory for the closed-loop control system; and
4) Verify the effectiveness of our newly proposed control scheme with 2-DoFs comparative simulation and experiments.

The reminder is presented as what follows. Some useful preliminaries are given in Section 2. Section 3 and 4 present the proposed control scheme design and stability analysis, while simulation and experimental verifications are given in Section 5 and 6. Finally, Section 7 concludes this paper.

2. Preliminaries

Several useful preliminaries are presented here which will be adopted afterwards.

Lemma 1. [49]. *The fractional integrator I^a_{b+} and I^a_{c-} using power a, R (a) > 0 are bounded in $L_p(b,c)$, $1 \le p \le \infty$:*

$$\left\|I^a_{b+}y\right\|_p \le K\left\|y\right\|_p,\ \left\|I^a_{c-}y\right\|_p \le K\left\|y\right\|_p,\ \left(K=\frac{(c-b)^{\Re(a)}}{\Re(a)|\Gamma(a)|}\right) \tag{1}$$

Lemma 2. [50]. *Suppose V(x) is a Lyapunov function with initial value of V_0, then the settling time for (2) is given as (3)*

$$\dot V(x)+aV(x)+bV^c(x)\le 0,\ a,\ b>0,\ 0<c<1 \tag{2}$$

$$T\le a^{-1}(1-c)^{-1}\ln(1+ab^{-1}V_0^{1-c}) \tag{3}$$

3. New CFONTSM control scheme design using TDE

3.1. Cable-driven manipulator dynamics

System dynamic structure is still needed to deduce the TDE-based control scheme despite its substantial model-free nature. Dynamics for cable-driven manipulators can be given as [2]

$$\mathbf{J}\ddot\theta+\mathbf{D}_{\rm m}\dot\theta=\tau_{\rm m}-\tau_{\rm s}(\mathbf{q},\dot{\mathbf{q}},\theta,\dot\theta) \tag{4}$$

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})+\mathbf{Fr}(\mathbf{q},\dot{\mathbf{q}})+\tau_{\mathbf{d}}=\tau_{\mathbf{s}}(\mathbf{q},\dot{\mathbf{q}},\theta,\dot\theta) \tag{5}$$

$$\tau_{\rm s}(\mathbf{q},\dot{\mathbf{q}},\theta,\dot\theta)=\mathbf{K}_{\rm s}(\theta-\mathbf{q})+\mathbf{D}_{\rm s}(\dot\theta-\dot{\mathbf{q}}) \tag{6}$$

where τ_m represents the torque vector provided by the drive motors while τ_s stands for joint compliance torque vector given in (6). $\mathbf{q}$ and θ stand for angular position vectors of the joints and motors, respectively. $\mathbf{J}$ is the inertia matrix of the drive motors, while $\mathbf{D}_m$ stands for corresponding damping matrix. $\mathbf{M}(\mathbf{q})$ is the mass-inertia matrix, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})$ stands for Coriolis/centrifugal forces matrix, $\mathbf{G}(\mathbf{q})$ and $\mathbf{Fr}(\mathbf{q},\dot{\mathbf{q}})$ are gravitational and friction force vectors, respectively. τ_d represents lumped unknown uncertainties including the external disturbance. $\mathbf{K}_s$ and $\mathbf{D}_s$ stand for joint stiffness and damping matrices, respectively.

The combined dynamics can be obtained by substituting (5) into (4) as

$$\tau_m=\mathbf{J}\ddot\theta+\mathbf{D}_m\dot\theta+\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})+\mathbf{Fr}(\mathbf{q},\dot{\mathbf{q}})+\tau_d \tag{7}$$

To apply TDE, (7) is transformed into following form as

$$\overline{\mathbf{M}}\ddot{\mathbf{q}}+\mathbf{N}=\tau_m \tag{8}$$

where $\overline{\mathbf{M}}$ is a diagonal constant matrix to be deigned and adjusted through simulations or experiments, $\mathbf{N}$ represents the remaining lumped unknown dynamics of the close-loop control system and can be given as

$$\mathbf{N}=\underbrace{(\mathbf{M}-\overline{\mathbf{M}})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})+\mathbf{Fr}(\mathbf{q},\dot{\mathbf{q}})+\tau_d}_{\text{Link dynamics element}}+\underbrace{\mathbf{J}\ddot\theta+\mathbf{D}_m\dot\theta}_{\text{Motor dynamics element}} \tag{9}$$

It can be observed from (9) that $\mathbf{N}$ is very complex. It mainly has two parts, the remaining link dynamics including the unknown external disturbance and the motor dynamics. Obviously, It can be extremely hard or laborious to obtain $\mathbf{N}$ with conditional methods.

3.2. Controller design with a new FONTSM and TDE

Define control errors as $\mathbf{e}=\mathbf{q}_d-\mathbf{q}$. To obtain satisfactory control performance under complex lumped disturbance, a new FONTSM manifold is proposed as

$$\mathbf{s}=\dot{\mathbf{e}}+\boldsymbol{\alpha}_1D^{\lambda_1}[\mathbf{sig}(\mathbf{e})^{\mathbf{b}_1}]+\boldsymbol{\alpha}_2D^{\lambda_2-1}[\mathbf{sig}(\mathbf{e})^{\mathbf{b}_2}] \tag{10}$$

where $\boldsymbol{\alpha}_i=diag(a_{i1},\dots,a_{in})$, $0<\lambda_{i1},b_{i1}\dots,\lambda_{in},b_{in}<1$, $i=1,2$ are control parameters to be designed.