Advances in Engineering Software 121 (2018) 13–25

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Research paper

Time delay control of cable-driven manipulators with adaptive fractional-order nonsingular terminal sliding mode☆

Yaoyao Wang[a,b,*], Fei Yan[a], Surong Jiang[a], Bai Chen[a]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, PR China
[b] the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, PR China

ARTICLE INFO

Index Terms:
Time delay control (TDC)
Time delay estimation (TDE)
Cable-driven manipulators
Adaptive control
Fractional-order (FO)
Nonsingular terminal sliding mode (NTSM)

ABSTRACT

For the high performance control of cable-driven manipulators, a novel time delay control (TDC) scheme with adaptive fractional-order nonsingular terminal sliding mode (AFONTSM) is presented and studied in this work. The presented control scheme uses time delay estimation (TDE) as its basic framework, which can effectively obtain a fascinating model-free feature just using the time-delayed information of the closed-loop control system. Afterwards, a novel AFONTSM control scheme is applied to provide with good comprehensive performance under complicated lumped disturbance in both reaching and sliding phases. The presented control method can be easily applied in real situations thanks to TDE, meanwhile satisfactory control performance can be guaranteed benefiting from the adopted AFONTSM error dynamics. Stability analysis is given based on Lyapunov stability theory. Finally, the effectiveness and superiorities of our newly designed control scheme are validated through 2-DOFs (degree of freedoms) comparative simulations and experiments.

1. Introduction

Recently, cable-driven manipulators have drawn lots of attention due to their unique superiorities for both industrial applications and academic researches. By arranging the drive units in or near the base instead of the joints and transmitting force/motion through cables, the cable-driven manipulators can ensure large payload-to-weight ratio, good flexibility and safety for interaction with people [1–3]. Benefiting from these superiorities, cable-driven manipulators now are broadly adopted in lots of fields, such as industrial manufacture, medical care and academic research [4–7].

To guarantee satisfactory work performance in all these applications, precise control of cable-driven manipulators is essential. But it is a much more challenging task to design high performance controller for the cable-driven manipulators than the traditional ones. The adoption of cables results in more complex system dynamics and lower stiffness, which greatly increases the difficulties for controller designing. Moreover, parametric uncertainties and time-varying lumped disturbance are also big problems. Thus, many efforts had been made to seek suitable control strategies for the systems containing joint elasticity and some exciting results had been achieved, such as fuzzy logic control [8], sliding mode (SM) control [9], state-dependent Riccati equation (SDRE) controller [10] and model predictive control [11]. Satisfactory control performance had been achieved with above-mentioned methods, which may be not suitable or easy to use in real situations due to the requirement of system dynamics or numerous control parameters.

Estimating and compensating the overall system dynamics with just the time-delayed signals, the time delay control (TDC) scheme can be a simple but efficient method to conquer aforementioned issues [12–17]. Usually, the TDC scheme contains two main parts, time delay estimation (TDE) part and robust controller part. The former is utilized as foundation framework of overall control scheme and can provide with a fascinating model-free feature. Meanwhile, the other part is used to provide with satisfactory comprehensive performance under complicated disturbance. Finally, the resulting TDC scheme is model-free and fit for complicated real applications benefiting from TDE and can ensure good comprehensive performance using the robust controller part. Benefiting from above superiorities, TDC schemes have been broadly adopted for many systems [18–22]. To further improve the control performance, sliding mode (SM) and terminal SM (TSM) control schemes had been immerged with TDE [23–30] leading to a fascinating robust model-free control scheme. However, the majority of proposed TDE-based SM/TSM control schemes are strictly limited to integer-

☆ This study was founded by the National Natural Science Foundation of China (51705243, 51575256), the Natural Science Foundation of Jiangsu Province (BK20170789) and the Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (GZKF-201606).
* Corresponding author at: College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, PR China.
E-mail address: yywang_cmee@nuaa.edu.cn (Y. Wang).

https://doi.org/10.1016/j.advengsoft.2018.03.004
Received 29 January 2018; Received in revised form 26 February 2018; Accepted 12 March 2018

order (IO) calculus and no fractional-order (FO) calculus were used. This may result in the restriction of control performance improvement. Meanwhile, FO controllers have been proved to be more effective than IO controllers for lots of systems [31–35] due to their flexibility in differentiation and integration. Recently, two novel TDE-based FO nonsingular TSM (FONTSM) control schemes were reported [36,37]. Great theoretical and experimental results had been presented in these works, but there are still some issues to be conquered. Fixed gains were adopted for the sign/saturation term and reaching law, which may result in poor control performance when the required task or external disturbance varies obviously. Meanwhile, extremely large gains may lead to unwanted chatters. Moreover, the FONTSM manifold given in [36,37] may result in poor dynamical performance due to the lacking of differential term, which, in turn, may lead to deterioration of control performance.

In this paper, above aspects are suitably settled. A novel TDC scheme with adaptive FONTSM (AFONTSM) is proposed and studied. The proposed control scheme contains three parts, a TDE utilized to enjoy its model-free nature, an improved FONTSM utilized to ensure finite-time convergence on the sliding mode phase and a combined adaptive reaching law applied to ensure satisfactory control performance under lumped disturbance in the reaching phase. The newly designed TDC scheme is model-free and suitable for practical situations thanks to TDE and can guarantee satisfactory control performance benefiting from the improved FONTSM error dynamics and combined adaptive reaching law. Stability analysis is presented using Lyapunov stability theory. Finally, some comparative simulations and experiments demonstrate the superiorities of our newly designed controller.

The main contributions of this paper are given as

(1) to propose a new TDC scheme with AFONTSM. By combining an improved FONTSM manifold, a fast-TSM-type reaching law and an adaptive law, the new AFONTSM part can ensure better control performance than those from [36,37];
(2) to present the integrated stability analysis and give the theoretical control error values; and
(3) to validate the superiorities of our newly proposed control scheme through simulations and experiments.

The rest is given as follows. Several preliminaries are presented in Section 2. The problem studied in this paper is briefly descripted in Section 3. Then, the proposed control scheme and corresponding stability analysis are presented in Sections 4 and 5. Afterwards, Sections 6 and 7 present the simulation and experimental studies. Finally, brief conclusions are given in 8.

2. Preliminaries

Some helpful preliminaries are given in this section.

Definition 1. [38]. The Riemann-Liouville fractional derivative and integration with ath-order of $f(t)$ with respective to t and terminal value t_0 are defined as follows:

$$D^a f(t) = \frac{d^a f(t)}{dt^a} = \frac{1}{\Gamma(p-a)}\frac{d^p}{dt^p}\int_{t_0}^{t}\frac{f(\tau)}{(t-\tau)^{a-p+1}}d\tau \tag{1}$$

$$_{t_0}I_t^a f(t) = \frac{1}{\Gamma(a)}\int_{t_0}^{t}\frac{f(\tau)}{(t-\tau)^{1-a}}d\tau \tag{2}$$

where $p-1 < a \le p$, $p \in N$, and $\Gamma(\bullet)$ is the Gamma function. For more details, please refer to [38].

Lemma 1. [38]. *The fractional integrators* I_{m+}^{ϑ}, I_{n-}^{ϑ}, $\Re(\vartheta) > 0$ *are bounded in* $L_p(m,n)$, $1 \le p \le \infty$ *as*

$$\left\|I_{m+}^{\vartheta}f\right\|_p \le \Omega\left\|f\right\|_p, \left\|I_{n-}^{\vartheta}f\right\|_p \le \Omega\left\|f\right\|_p \left(\Omega = \frac{(n-m)^{\Re(\vartheta)}}{\Re(\vartheta)|\Gamma(\vartheta)|}\right) \tag{3}$$

Lemma 2. [39]. *For any three real scalars* x_1, x_2, x_3, (4) *will stand with any scalar* $a \ge 0.5$ *under* $x_1 + x_2 = x_3$

$$x_1x_2 \le -\frac{2a-1}{2a}x_1^2 + \frac{a}{2}x_3^2 \tag{4}$$

Lemma 3. [39]. *Considering , suppose* (5) *stands with a continuous function* $V(y)$, *scales* $a > 0$, $0 < b < 1$ *and* $0 < c < \infty$

$$\dot{V}(y) \le -aV^b(y) + c \tag{5}$$

Then, is defined as practical finite-time stable (PFS) and its states will be finite-time bounded as

$$\lim_{d\to d_0} y \in \left(V^b(x) \le \frac{c}{(1-d)a}\right) \tag{6}$$

where $0 < d_0 < 1$. The time needed to arrive at (6) is bounded as

$$T \le \frac{V^{1-b}(y_0)}{a(1-b)d_0} \tag{7}$$

where $V(y_0)$ is the initial value of $V(y)$.

Lemma 4. [40]. *For arbitrary real numbers* $x_i, i = 1,\ldots,n$ *and* $0 < a \le 1$, *following inequality will hold*

$$(|x_1|+\cdots+|x_n|)^a \le |x_1|^a + \cdots + |x_n|^b \tag{8}$$

3. Problem description

The following n-DOFs cable-driven manipulator is considered

$$J\ddot{\theta} + D_M\dot{\theta} = \tau_M - \tau_s \tag{9}$$

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{Fr}(\mathbf{q}, \dot{\mathbf{q}}) + \tau_d = \tau_s \tag{10}$$

$$\tau_s = \mathbf{K}_s(\theta - \mathbf{q}) + \mathbf{D}_s(\dot{\theta} - \dot{\mathbf{q}}) \tag{11}$$

where $\boldsymbol{\tau}_M$ and $\boldsymbol{\tau}_S$ are the drive motor input torque and joint compliance torque in (11). $\mathbf{q}$ and $\boldsymbol{\theta}$ are angular displacement vectors of the joints and motors, respectively. $\mathbf{J}$ stands for the drive motor inertia matrix, while D_M represents the damping matrix. $\mathbf{M}(\mathbf{q})$ stands for the mass-inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is Coriolis/centrifugal forces matrix, $\mathbf{G}(\mathbf{q})$ and $\mathbf{Fr}(\mathbf{q}, \dot{\mathbf{q}})$ represent gravitational and friction force vectors, respectively. $\boldsymbol{\tau}_d$ stands for external disturbance. $\mathbf{K}_s$ and $\mathbf{D}_s$ are joint stiffness and damping matrix, respectively.

Given the desired joint position trajectory $\mathbf{q}_d$, the objective is to find a proper model-free control input $\boldsymbol{\tau}_M$ such that the output joint position $\mathbf{q}$ can tracking $\mathbf{q}_d$ as accuracy as possible.

4. TDC scheme design with AFONTSM

4.1. Integrated system dynamics

Integrated system dynamics containing motor dynamics and joint stiffness can be obtained by substituting (10) into (9) as

$$\begin{aligned}\tau_M = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{Fr}(\mathbf{q}, \dot{\mathbf{q}}) + \tau_d \\ + \mathbf{J}\ddot{\theta} + \mathbf{D}_M\dot{\theta}\end{aligned} \tag{12}$$

To conveniently use TDE technique, (12) is rewritten as

$$\widetilde{\mathbf{M}}\ddot{\mathbf{q}} + \boldsymbol{\mu} = \tau_M \tag{13}$$

where $\widetilde{\mathbf{M}}$ stands for a constant matrix and is usually tuned by simulations or experiments. Meanwhile, $\boldsymbol{\mu}$ represents the remaining system dynamics expect $\widetilde{\mathbf{M}}\ddot{\mathbf{q}}$ and can be defined as