带头人陈柏代表性著作

代表作 1：Development of a Minimal-Intervention-Based: Admittance Control Strategy for Upper Extremity Rehabilitation Exoskeleton

Development of a Minimal-Intervention-Based Admittance Control Strategy for Upper Extremity Rehabilitation Exoskeleton

Qingcong Wu, Xingsong Wang, Bai Chen, and Hongtao Wu

***Abstract*—The applications of robotics to the rehabilitation training of neuromuscular impairments have received increasing attention due to their promising prospects. The effectiveness of robot-assisted training directly depends on the control strategy applied in the therapy program. This paper presents an upper extremity exoskeleton for the functional recovery training of disabled patients. A minimal-intervention-based admittance control strategy is developed to induce the active participation of patients and maximize the use of recovered motor functions during training. The proposed control strategy can transit among three control modes, including human-conduct mode, robot-assist mode, and motion-restricted mode, based on the real-time position tracking errors of the end-effector. The human–robot interaction in different working areas can be modulated according to the motion intention of patient. Graphical guidance developed in Unity-3-D environment is introduced to provide visual training instructions. Furthermore, to improve training performance, the controller parameters should be adjusted in accordance with the hemiplegia degree of patients. For the patients with severe paralysis, robotic assistance should be increased to guarantee the accomplishment of training. For the patients recovering parts of motor functions, robotic assistance should be reduced to enhance the training intensity of effected limb and improve therapeutic effectiveness. The feasibility and effectiveness of the proposed control scheme are validated via training experiments with two healthy subjects and six stroke patients with different degrees of hemiplegia.**

***Index Terms*—Admittance control strategy, human–robot interaction, minimal-intervention-based, rehabilitation, upper extremity exoskeleton.**

I. Introduction

With the rapid increase of elderly population, more and more patients suffer from nervous and muscular diseases, such as stroke and spinal cord injury, which lead to residual impairments and long-term disability. According to the recent statistical results of the World Health Organization, there are more than 15 million stroke patients in the world and three million new occurrences every year. Stroke has become the third leading cause of death worldwide after cardiovascular disease and cancer, accounting for nearly 10% of all deaths. About two-thirds of the stroke patients survive, however, more than 80% of them may experience hemiparesis. These survivors require a prolonged physical therapy to recover motor functions in activities of daily living (ADL). The research of neurological rehabilitation suggests that repetitive motor activity has positive effects on improving movement co-ordination and avoiding muscle atrophy. Further, the therapeutic effect is mainly determined by the intension, repeatability, task-oriented quality, and sustainability of rehabilitation training [1]. The one-to-one assisted training, which requires the physiotherapist to manually move and knead the affected limb of patient, is common in the clinical therapeutics of hemiparesis. However, this conventional method is time consuming, labor-intensive, and costly. Besides, the training performance is affected by the ability of therapist [2].

In recent decades, the application of robotic system to the rehabilitation treatment of neuromuscular impairment has received increasing attention from around the world [3]–[5]. Robotic systems are quite suitable for rehabilitation training after stroke, as they can overcome some of the aforementioned limitations of therapist treatment. Robot-assisted therapy is capable of delivering long-endurance and high-intensity therapeutic training with programmable control strategies and streamlining the rehabilitation process. Besides, it enables the therapist to obtain objective and quantitative evaluations of training performance and, furthermore, optimize the therapy strategy to improve rehabilitative efficacy. So far, many kinds of assistive or therapeutic robots have been developed for individuals who are disabled. Among these robotic systems, the upper extremity rehabilitation exoskeletons, which resemble the human arm anatomy and work in parallel with the affected limb, have attracted plenty of interest of widespread researchers, such as RUPERT [6], BONES [7], ARMin [8], CAREX [9], IntelliArm [10], and UL-EXO7 [11].

The effectiveness of robot-assisted rehabilitation treatment is directly determined by the control methods applied in the therapy program. Various kinds of control strategies have been developed for the upper extremity rehabilitation

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代表作 2：Modeling, online identification, and compensation control of single tendon sheath system with time-varying configuration

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Modeling, online identification, and compensation control of single tendon sheath system with time-varying configuration

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ABSTRACT

Tendon sheath system (TSS) has been widely used in many applications with strict spatial limitations due to its flexibility, dexterity, and remote transmission ability. However, the inherent configuration-dependent nonlinearities between tendon and sheath seriously degrade the transmission performance and result in inaccurate force and position control. In this paper, the force and position transmission models of single TSS with arbitrary route configurations and terminal loads are developed based on the analysis of system friction and deformation. A tendon-sheath-based bending sensor is proposed for the online identification of accumulated bending angle. To enhance the accuracies of force control and position control with time-varying configuration, two control strategies are developed for the friction and deformation compensation without sensory feedback from distal end. An experimental setup of tendon sheath actuation is established to gain insights into the force and position transmission processes and evaluate the effectiveness of the developed transmission models and compensation controllers. The results of model validation experiments with sinusoidal force input show that the modeling errors of force and position transmission are less than 5% and 2.5%, respectively. Moreover, the trajectory tracking experiments and frequency response experiments are carried out, and the results demonstrate the feasibility of the proposed identification strategy and compensation controllers in improving control accuracy and ensuring control bandwidth of single TSS with time-varying bending angle.

1. Introduction

Tendon sheath system (TSS), also called as Bowden cable system or cable conduit mechanism, is a typical flexible transmission system widely used in many applications such as minimally invasive surgical robot [1–3], robotic dexterity hands [4], rescue robots [5], exoskeletons [6–10], flexible endoscopic system [11,12], and bilateral teleoperation robot [13]. TSS generally consists of a hollow slender helical coil wire acting as the outer sheath and an internal cable acting as the inner tendon [14]. It is capable of providing high and remote power transmission through narrow and tortuous pathways with arbitrary curvatures and simplifying the overall mechanical structure design of robotic system. However, due to cable compliance and the friction between inner tendon and outer sheath, the TSS suffers from many highly nonlinear problems like hysteresis, tension attenuation, tendon slacking, motion backlash, and direction-dependent behavior [15]. These undesirable

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代 表 作 3 ： Adaptive Time-Delay Control for Cable-Driven Manipulators With Enhanced Nonsingular Fast Terminal Sliding Mode

Adaptive Time-Delay Control for Cable-Driven Manipulators With Enhanced Nonsingular Fast Terminal Sliding Mode

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***Abstract*—For high control performance of cable-driven manipulators, we design a new adaptive time-delay control (ATDC) using enhanced nonsingular fast terminal sliding mode (NFTSM). The proposed ATDC uses time-delay estimation (TDE) to acquire the lumped dynamics in a simple way and founds a practical model-free structure. Then, a new enhanced NFTSM surface is developed to ensure fast convergence and high control accuracy. To acquire good comprehensive performance under lumped uncertainties, in this article we propose a novel adaptive algorithm for the control gain, which can regulate itself based on the control errors timely and accurately. Benefitting from the TDE and the proposed enhanced NFTSM surface and adaptive control gain, our proposed ATDC is *model-free, fast response*, and *accurate*. Theoretical analysis concerning system stability, and control precision and convergence speed are given based on Lyapunov theory. Finally, the advantages of our ATDC over existing methods are verified with comparative experiments.**

***Index Terms*—Adaptive time-delay control (ATDC), cable-driven manipulators, nonsingular fast terminal sliding mode (NFTSM), time-delay estimation (TDE).**

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I. Introduction

RECENTLY, cable-driven manipulators have attracted lots of attentions due to their special properties, including large load-to-weight ratio and high safety for robot–human interactions [1], [2]. But the application of cable-driven technology also brings about additional control difficulties, such as large nonlinearities, flexible joints and parametric uncertainties. Hence, it is still an open challenge to achieve high control performance for cable-driven manipulators up to now.

Many efforts have been made to guarantee good control performance for the robotic systems, especially those with flexibilities [3]–[8]. In [5], a practical control was proposed to realize multivariable full-state tracking control of flexible joint robots, which used a singular perturbation technique. In [6], a boundary controller with input backlash was proposed to handle the complex control issues for a flexible robotic manipulator. Then, the validity was proved by theoretical analysis, simulations and experiments. To achieve satisfactory performance of cable-driven parallel robots, two novel synchronization controllers were designed and experimented [7]. In [8], the n-dimensional discretized model of flexible manipulators was presented using assumed model scheme. Then, a novel neural network control was proposed based on above model to obtain good control performance. In aforementioned methods, system dynamics or complicated estimation algorithms are obligatory. This will be difficult for applications with time-varying tasks and uncertainties.

To obtain a simple but efficient control for complex practical systems, many scholars have turned to the time-delay control (TDC) scheme [9]–[16]. By using the time-delay estimation (TDE) to acquire the lumped dynamics, TDC can provide a practical model-free structure. Due to this apparent point of attraction, TDC has been applied for many practical systems, such as manipulators [17]–[20], underwater robots [21], shape memory alloy actuators [22], humanoid robots [23], and lower limb exoskeleton [24]. In the meantime, utilization of TDE will generate estimation errors especially under fast time-varying dynamics. Thus, robust control strategies are often required to further enhance the performance of TDC. As an effective tool to handle complex uncertainties, sliding mode control and its variants have drawn much attention [25]–[29]. Thus, they have been broadly emerged with TDE for high performance under

代表作 4：Time-Delay Control Using a Novel Nonlinear Adaptive Law for Accurate Trajectory Tracking of Cable-Driven Robots

Time-Delay Control Using a Novel Nonlinear Adaptive Law for Accurate Trajectory Tracking of Cable-Driven Robots

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***Abstract*—In this article, we propose a novel adaptive time-delay control (ATDC) for accurate trajectory tracking of cable-driven robots. The designed ATDC utilizes time-delay estimation (TDE) to estimate the lumped dynamics of the system and provides an attractive model-free structure. Then, a robust control is designed for ATDC with fractional-order nonsingular terminal sliding mode (FONTSM) dynamics. Afterward, a novel nonlinear adaptive law is proposed for the control gains to improve the control performance. Thanks to TDE and FONTSM dynamics, the proposed ATDC is model free and highly accurate. Benefiting from the proposed nonlinear adaptive law, suppression of chattering issue and enhanced control performance have been obtained simultaneously. Stability is analyzed based on the Lyapunov approach. Then, practical experiments have been performed to illustrate the advantages of the proposed ATDC.**

***Index Terms*—Cable-driven robots, nonlinear adaptive law, time-delay control (TDC), time-delay estimation (TDE), trajectory tracking.**

NOMENCLATURE

θ, $\mathbf{q}$	Position vectors of motor and joint.
J_m, D_m	Inertia and damping matrices of motors.
$\mathrm{M}(\mathrm{q})$, $\mathrm{C}(\mathrm{q}, \dot{\mathrm{q}})$, $\mathrm{G}(\mathrm{q})$, $\mathrm{Fr}(\mathrm{q}, \dot{\mathrm{q}})$	Inertia and Coriolis matrices, gravity and friction force vectors for rigid robot part.
D_s, K_s	Damping and stiffness matrices of joint.
$\boldsymbol{\tau}_d$, $\boldsymbol{\tau}_s$, $\boldsymbol{\tau}_m$	Torque vectors generated by disturbance, joint compliance. and drive motors.
$\bar{\bullet}$, $\hat{\bullet}$	Symbol $^-$ / ^ denotes the constant/adaptive parameter.
$\bullet_t$, $\bullet_{(t-L)}$,	Value of $\bullet$ under the moment t and $(t-L)$.
$\overline{\mathrm{M}}$, $\hat{\mathrm{M}}$	Predesigned constant/adaptive diagonal matrix with positive elements.
$\mathbf{k}_p$, $\mathbf{k}_d$, K_p, K_d	Positive control gains for PD dynamics.
$\boldsymbol{\varepsilon}$	TDE error, defined as $\varepsilon_i = \overline{M}_{ii}^{-1}(h_i - \hat{h}_i)$.
$\eta_{i,\max}$, $\eta_{i,\mathrm{mid}}$	Predesigned constant maximum value of $\hat{\eta}_i$, and $\eta_{i,\mathrm{mid}} = \eta_{i,\max}/2$.
$\mathbf{k}_{1\text{-}6}$, $\boldsymbol{\alpha}_{1,2}$, $\boldsymbol{\beta}_{1,2}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}_{1,2}$, $\boldsymbol{\lambda}_{1,2}$, $\boldsymbol{\rho}$, $\boldsymbol{\varphi}$, $\boldsymbol{\Omega}$, $\boldsymbol{\omega}$, $\boldsymbol{\sigma}_{1,2}$, $\boldsymbol{\sigma}$, K_s, $\boldsymbol{\Delta}$, $\overline{\boldsymbol{\Delta}}$, $\overline{\mathrm{k}}$, $\overline{\mathrm{K}}$	Positive control gains for our/Wang's/Baek's/Jin's ATDC schemes, the ith elements of $\boldsymbol{\alpha}_{1,2}$, $\boldsymbol{\beta}_{1,2}$, and $\boldsymbol{\rho}$ are within $(0, 1)$ and k_{5i}, $\sigma_i > 1$.
$\mathbf{sig}(\mathbf{x})^{\mathbf{y}}$	For any $\mathbf{x} = [x_1, \ldots, x_n]$, $\mathbf{y} = [y_1, \ldots, y_n]$, $\mathbf{sig}(\mathbf{x})^{\mathbf{y}} = [|x_1|^{y_1}\mathrm{sgn}(x_1), \ldots, |x_n|^{y_n}\mathrm{sgn}(x_n)]$.

I. INTRODUCTION

A. Motivation and Incitement

ACCURATE trajectory tracking of cable-driven robots is a challenging task because of the large nonlinearities and parametric uncertainties [1], [2]. To this end, scholars have proposed several robust control methods for the system with flexibilities, such as adaptive control [3], sliding mode control [4], and intelligent control [5], [6]. Abovementioned methods require either system dynamics or complex approximation algorithms, which is difficult to employ under practical applications. What we require is an efficient but simple control for the cable-driven robots.

For this challenging task, time-delay control (TDC) was proposed and employed [7]–[13]. Using the time-delay signals to estimate the lumped dynamics, time-delay estimation (TDE) guarantees an attractive model-free structure for TDC. Owing to this feature, TDC has been broadly employed for many systems, such as robot manipulators [14], [15] and humanoid robots [16]. Meanwhile, the application of TDE will often result in estimation errors. Thus, robust controls are usually combined with TDE to further enhance the control performance under time-varying

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代表作 5：Model-free continuous nonsingular fast terminal sliding mode control for cable-driven manipulators

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Practice article

Model-free continuous nonsingular fast terminal sliding mode control for cable-driven manipulators

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ABSTRACT

This work proposes a model-free robust control for cable-driven manipulators with disturbance. To achieve *accurate*, *singularity-free* and *fast* dynamical control performance, we design a new NFTSM surface utilizing a new continuous TSM-type switch element. By replacing the integral power with fractional one for the error dynamics, the designed TSM-type switch element can effectively enhance the dynamical performance of the NFTSM surface. Time-delay estimation (TDE) technique is applied to cancel out complicated nonlinear dynamics guaranteeing an excellent *model-free* scheme. Thanks to the designed NFTSM surface, adopted reaching law and TDE, our control can provide good comprehensive control performance effectively. Stability and comparisons of control precision and convergence speed have been theoretically analyzed. Finally, comparative experiments were conducted to prove the superiorities of our control.

1. Introduction

Benefitting from the good capability for automatic tasks, the robot manipulators have fascinated both engineers and scholars for many years. For traditional robot manipulators, the drive units are placed at joints leading to large inertia and high stiffness. Precise tracking control may be obtained with this design, but this may be unsafe for working around human. To effectively cope with above problems, the cable-driven technique was brought into robot manipulators. Rearranging the drive units and adopting cables to transmit motion and force, the cable-driven mechanisms have lower inertia, higher flexibility and better safety for working around human [1,2].

Accurate tracking performance is usually required for lots of tasks, which is more difficult for cable-driven manipulators. The major difficulties consist of much more complicated system dynamics, larger nonlinearities and joints flexibility. Many efforts have been made to achieve satisfactory performance for the systems with flexibilities [3–7]. Usually, relative precise dynamic model information is required to realize accurate trajectory tracking control, like adaptive control, inverse dynamic control, sliding mode (SM) control [8–15]. However, the precise dynamic model is sometimes very difficult to acquire, meanwhile calculations of system dynamics can be extremely complicated and computationally burden. Therefore, some intelligent controllers have been applied to effectively settle above problems [16–18]. Implementation of above intelligent controllers is also not easy, because they usually require numerous parameters or complex parameter-tuning algorithms. In short, above methods require either exact robot dynamic model or numerous parameters for model estimation, which is usually unsuitable for practical applications.

To ensure a simple but effective method for such complicated practical applications, we adopt the time-delay estimation (TDE) technique [19,20]. By estimating system dynamics with only the system states, TDE can guarantee an excellent *model-free* scheme. Thanks to this scheme, TDE has been broadly used [21–26]. There are usually two parts in above-mentioned TDE-based control methods: TDE and robust control. The former is used to achieve the model-free feature under lumped uncertainties, while the latter is adopted to obtain the desired error dynamics. At the beginning, linear error dynamics was combined with TDE [19]. Later, terminal sliding mode (TSM) control was combined with TDE to achieve finite-time control performance and high tracking accuracy [22]. Thanks to the advantages of TSM [27], the TDE-based TSM control schemes have better performance than the one with linear error dynamics; meanwhile it still remains the easiness for practical applications. Afterwards, several TDE-based TSM controls were proposed and investigated [28–34].

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代表作 6：Neural-network-enhanced torque estimation control of a soft wearable exoskeleton for elbow assistance

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Neural-network-enhanced torque estimation control of a soft wearable exoskeleton for elbow assistance☆

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ABSTRACT

Soft wearable exoskeletons are a new approach for the applications of power assistance and rehabilitation training. In the present work, a neural-network-enhanced torque estimation controller (NNETEC) is proposed for a soft wearable elbow assistance exoskeleton with compliant tendon-sheath actuator. A comprehensive overview for the major components of the soft exoskeleton is introduced. The locations of anchor points are optimized via the maximum-stiffness principle. The NNETEC strategy is developed by fusing the feedback signals from surface electromyography (sEMG) sensors, inertial measurement units, force sensors, and motor encoder. It consists of a joint torque estimation module to identify the elbow torque of wearer based on Kalman filter, a neural-network adjustment module to recognize human motion intention, and a proportional-integral-derivative controller with hybrid position/torque feedbacks. Further experimental investigations are carried out by five volunteers to validate the effectiveness of the proposed soft elbow exoskeleton and control strategy. The results of the dumbbell-lifting experiments with various weights and frequencies demonstrate that, when compared with the proportional control strategy and the sEMG-based assistive control strategy without neural-network adjustment, the developed NNETEC method can achieve higher power assistance efficiency.

1. Introduction

With the rapid development of aging society, more and more elderly persons and patients suffer from the muscular and nervous diseases leading to serious motor dysfunction problems, such as spinal cord injury, paralysis, and stroke. The surviving disabled patients need prolonged physical treatments to improve muscle strength and recover motor functions in activities of daily living (ADL). The one-to-one manual treatment is common in the clinical therapies, which requires the physical therapist to manually assist patient when performing progressive resistive training. However, there are many limitations of this traditional approach, such as high labor intensity, high treatment cost, long time consumption, and insufficient physician resources [1]. In recent years, there has been growing interest in researching the exoskeleton technology to assist the rehabilitation training of disabled subjects. Exoskeleton robots have complex mechanical structure imitating the skeleton of human body [2]. It can be worn on the affected limb of operator to provide biological joint assistive torque and enhance movement capability. Exoskeleton-based therapy is capable of providing high-efficiency, long-endurance, and goal-directed treatments with various programmable control schemes. The recovery progress of patients can be measured and recorded accurately via the integrated sensing system [3]. Besides medical application, exoskeletons have also been widely applied in many other areas, such as human power amplification, haptic interaction, military operation and so on [4].

Most of the existing wearable exoskeletons are made up of rigid links working in parallel with human limbs. Brahim et al. developed a rigid exoskeleton with seven degrees of freedom (DOFs), named ETS-MARSE, for the passive rehabilitation training of superior extremity [5]. Liu et al. developed a novel portable powered exoskeleton with variable stiffness, called PVSED, for elbow movement assistance [6]. Zhang and Huang designed a rigid lower-back augmentation exoskeleton to provide spinal support and assist in industrial material handling tasks [7]. Wu et al. proposed a gravity-balanced upper limb rehabilitation exoskeleton with Bowden cable actuation [8]. Besides, many other rigid-type exoskeletons have been developed, such as ChARMin [9], NEUROExos [10], BONES [11], IntelliArm [12], BIAVE [13], and WRES [14]. However, the rigid nature of these exoskeletons presents many ongoing challenges in practical application, such as large structure dimension, heavy body weight, and high-energy consumption. In addition, the misalignment between robot joints and biological joints will cause safety hazards and discomfort during physical human-robot interaction.

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代表作 7：A new practical robust control of cable-driven manipulators using time-delay estimation

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A new practical robust control of cable-driven manipulators using time-delay estimation

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Summary

In this paper, a new practical robust control scheme is proposed and investigated for the cable-driven manipulators under lumped uncertainties. There are three parts in the proposed method, ie, a time-delay estimation (TDE) part, a modified super-twisting algorithm (STA) part, and a fractional-order nonsingular terminal sliding mode (FONTSM) error dynamics part. The TDE uses intentionally time-delayed system signals to estimate the lumped dynamics of the system and ensures an attractive model-free control structure. The STA is applied to guarantee high performance and chattering suppression simultaneously in the reaching phase. The FONTSM error dynamics is utilized to obtain fast convergence and strong robustness in the sliding mode phase. Thanks to the above three parts, the proposed control scheme is model free and can ensure high control performance under lumped uncertainties. The stability considering the FONTSM error dynamics and modified STA scheme is analyzed. Comparative simulation and experiments were conducted to demonstrate the effectiveness and superiorities of the newly proposed control scheme. Corresponding experimental results show that our newly proposed control scheme can provide more than 20% improvement of the steady control accuracy under three different reference trajectories.

KEYWORDS

cable-driven manipulators, fractional order, model free, nonsingular terminal sliding mode, super-twisting algorithm (STA), time-delay estimation (TDE)

1 | INTRODUCTION

Robot manipulators have been widely utilized in many practical fields benefitting from their excellent capability to execute automatic tasks.[1-4] Usually, the drive motors are directly installed in the joints to simplify the system structure and obtain good control accuracy, which in turn will bring in high stiffness and big moving inertia. This design performs well for the industrial applications, but it will not be safe for the physical interactions with human due to the high stiffness and large moving mass. Therefore, the cable-driven manipulators were proposed and utilized to efficiently settle the above issue.[5] Compared with the widely used classical robot manipulators, the cable-driven ones have much lower stiffness and smaller moving mass, which can effectively guarantee the safety for physical interactions with human. Due to above obvious advantages, cable-driven manipulators have been widely used in medical care, flexible manufacturing, and academic studies.[6-12]

代表作 8：A New Adaptive Time-Delay Control Scheme for Cable-Driven Manipulators

A New Adaptive Time-Delay Control Scheme for Cable-Driven Manipulators

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***Abstract*—This paper proposes a new adaptive time-delay control (ATDC) scheme for cable-driven manipulators. The proposed ATDC scheme contains three elements, i.e., time-delay estimation (TDE), injected dynamics, and adaptive laws. The TDE utilizes intentionally time-delayed signals to estimate the unknown system dynamics and brings a fascinating model-free nature. The injected dynamics employ a fractional-order nonsingular terminal sliding mode (FONTSM) manifold and a fast-TSM-type reaching law, thus it can ensure fast dynamical response and high tracking accuracy in both sliding mode and reaching phases. The adaptive laws are utilized to obtain good robustness and effective suppression of the chatters simultaneously. Moreover, the *continuous* and *chatter-free* adaptive gains are used to enhance the control performance under time-varying disturbances. The tracking error is proved to be uniformly ultimately bounded (UUB) using Lyapunov approach. Finally, the superiorities of the proposed ATDC scheme are demonstrated by three experiments using a cable-driven manipulator.**

***Index Terms*—Adaptive control, cable-driven manipulators, fractional-order, nonsingular terminal sliding mode (NTSM), time-delay control (TDC).**

I. Introduction

RECENTLY, cable-driven manipulators have been gradually utilized in a growing number of applications thanks to their unique advantages. By moving the motors from joints to the base and transmitting motion/force through cables, the cable-driven manipulators can obtain smaller moving inertial, higher load-to-weight ratio, better flexibility than the traditional robot manipulators [1]–[3]. However, the high-performance tracking control of cable-driven manipulators is still a challenging job due to the complex system dynamics and time-varying lumped disturbances. Some robust control schemes have been proposed to obtain satisfactory control performance for the robots with flexible joints and the above-mentioned difficulties, such as sliding mode (SM) control [4], adaptive control [5], fuzzy logic control [6], neural network control [7], [8], etc. Although these control schemes have successfully guaranteed inspiring results, they are still not easy to use in practical applications due to the requirement of system dynamics or complicated estimation algorithms.

Time-delay control (TDC) is a simple but effective method to overcome the aforesaid difficulties. The core element of the TDC scheme is the time-delay estimation (TDE) technique, which uses intentionally time-delayed signals to estimate the lumped system dynamics and brings a fascinating model-free feature. By virtue of this obvious advantage, the TDC scheme has been widely used in many systems [9]–[14], such as robot manipulators [15]–[17], underwater vehicles [18]–[20], lower extremity exoskeletons [21], Euler-Lagrange systems [22], robots with flexibilities [2], [13], [23], etc. Nevertheless, the employment of time-delayed signals will inevitably bring about estimation errors, i.e., TDE errors, in practical applications. When hard nonlinearities appear, for instance, saturation and Coulomb friction, the TDE errors will obviously increase and result in serious control performance degeneration. Therefore, the TDC scheme is usually used as a framework to take advantage of its model-free feature. Meanwhile, other robust control strategies are utilized to acquire high accuracy and strong robustness, such as SM control [24]–[28], terminal SM (TSM) control [29]–[31], adaptive robust control [23], [32]–[35]. Thanks to the model-free TDE technique and the employed robust control strategies, the TDE-based control schemes can guarantee high control performance in a simple way.

However, most of the existing TDE-based control schemes are strictly restricted to constant control gain $\bar{M}$, which means fixed $\bar{M}$ is used in all situations. This may result in obvious control performance deterioration when time-varying complex disturbances appear. As widely demonstrated in existing works [15]–[18], [36]–[38], the control accuracy is approximately proportional to the control gain $\bar{M}$. Therefore, higher control accuracy and faster dynamical response may be obtained with larger

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