ARTICLE IN PRESS

ISA Transactions xxx (2018) 1–11

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Sliding mode control for a two-joint coupling nonlinear system based on extended state observer

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A R T I C L E I N F O

Article history:
Received 6 April 2017
Revised 24 October 2017
Accepted 29 December 2017
Available online XXX

Keywords:
Coupling nonlinear systems
Sliding mode control (SMC)
Extended state observer (ESO)
Pneumatic artificial muscle (PAM)

A B S T R A C T

A two-joint coupling nonlinear system driven by pneumatic artificial muscles is introduced in this paper. A sliding mode controller with extended state observer is proposed to cope with nonlinearities and disturbances for the two-joint coupling nonlinear system. In addition, convergence of the extended state observer is presented and stability analysis of the closed-loop system is also demonstrated with the sliding mode controller. Lastly, some experiments are carried out to show the reality effectiveness of the proposed method.

1. Introduction

Pneumatic robots have been increasingly used for automation industry in recent years. Attributes of low cost and long durability for pneumatic servo systems have extended the automation market share of pneumatic robots [1]. Pneumatic servo systems are not only used for automation industry but also used for hazardous operating circumstances, flexible manipulators and bionic robots [2]. As important pneumatic bionic products, PAMs which are designed to emulate biological muscles have some properties such as large output force-volume/force-weight ratio, green, etc. As environment friendly products, PAMs have strong nonlinearities which are caused by compressibility of air and elasticity of embedded tube. The aforementioned properties of PAMs make it difficult to have good control performances for PAM-actuator robots [3]. With the rapid development of networks and computer technologies, lots of concentrations are attracted by networked control systems [4–6]. PAMs are also considered as a pneumatic manipulator in networked control systems [7]. The control difficulties not only come from PAMs actuators' nonlinearities but also lie in tendon transmission coupling. It is a good idea to adopt tendons for pulling the control object due to space-saving advantages. Tendon driving mechanisms are widely used in lightweight humanoid robots, however, coupling tendon manner degrades the merits of control performance in PAM-actuator systems [8].

There are many research theories to solve those positioning control problems of PAM-actuator systems. Proportion-integration-differentiation (PID) controllers are designed for certain mechanisms driven by PAMs. For example, a fuzzy adaptive PID controller is proposed to finely tune controller gains under different operating circumstances [9]. Moreover, a nonlinear PID controller with neural networks is introduced for a 2-axe PAM manipulator to address nonlinearities and time-varying problems [10], in which parameter optimal has been realized but decoupling has not been considered for coupling joints. PID controllers may be sensitive to unmodeled changes due to state varies and disturbances from systems or environments [11]. Inverse dynamics feedforward control is adopted to establish a strongly model-based controller to polish response performances [12]. A similar model-based hybrid computed torque approach is proposed for a high-speed manipulator [13]. Those control methods heavily rely on the accuracies of systems' model, however, pneumatic systems driven by PAMs are difficult to obtain the

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https://doi.org/10.1016/j.isatra.2017.12.027
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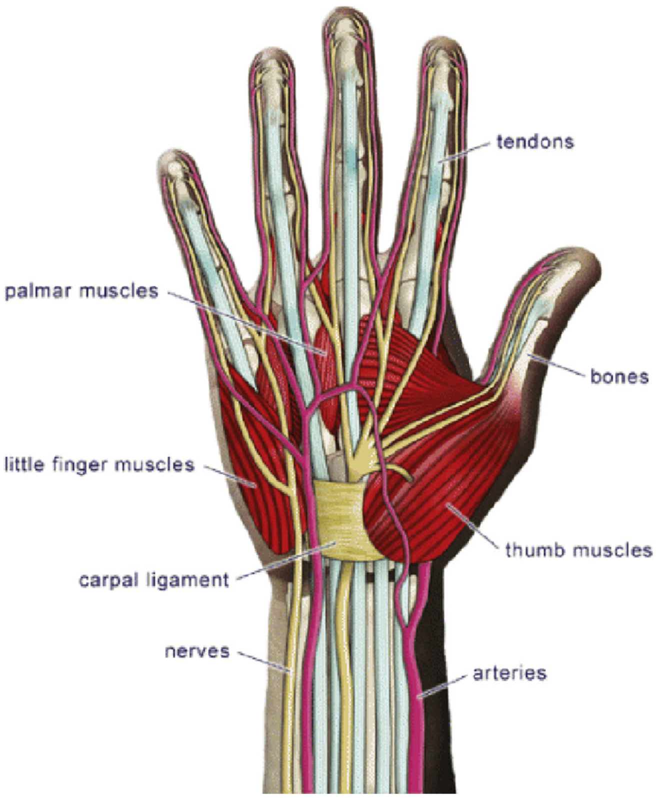


Fig. 1. The anatomy configuration of human hand.

accurate systems' model due to those great nonlinear characteristics [14]. Some robust control strategies are employed to tackle unmodelled dynamics and nonlinearities in PAM actuators. An adaptive robust controller is introduced for a parallel manipulator actuated by PAMs with compensating uncertainties and nonlinearities of the parallel manipulator [15]. An adaptive extended active observer is proposed to estimate force and state in nonlinear robot systems [16].

As a robust control strategy, SMC is widely applied and developed by a lot of researchers to a variety of systems [17]. Generally, SMC is applied to solve against model errors and uncertain disturbances, which are close to pneumatic system's time-varying and strong nonlinearity characteristics. In Ref. [18], an indirect sliding mode controller is presented to control pneumatic artificial muscles, which have a good position-tracking performance. In order to deal with the time-varying nonlinear dynamics and external disturbances, a sliding mode controller with Fourier neural networks is conducted for pneumatic actuator system, besides, the H_∞ technology is added in the control system to curb the vibration of proportional directional control valve and adaptive approximation error [19]. Time-delay is an ingrained issue inherited in pneumatic systems, a controller which combines adaptive fuzzy sliding mode control with adaptive predictor is designed to attenuate the time delay obstacle in Ref. [20]. An integral sliding mode controller is introduced to a servo pneumatic system without an exact friction model, showing a good robustness even though parameter changes [21]. As literature cited shows, sliding mode controller is an appropriate control method to be applied in pneumatic systems due to its robustness characteristic. Furthermore, extended state observer is the centerpiece of active disturbance rejection control(ADRC) theory which was proposed by Jingqing Han in last 1980s. ADRC argues that all nonlinearities and disturbances in control system is considered as a total disturbance, which can be observed and estimated by ESO, furthermore, the observation value is eliminated in controller to resist the disturbances [22,23]. Both Lyapunov [24] and self-stable region [25] methods are utilized to analyze its convergence and estimate errors, but the results are conservative [26]. In Ref. [27], a proof is given that the output of a closed-loop system can approach its ideal trajectory in an entire transient process despite unknown nonlinear dynamics. Many generalized convergence results were obtained recently for single-input-single-output (SISO) and multiple input-multiple-output (MIMO) systems in Refs. [28] and [29], respectively. However, many assumptions are made in these results, and it is difficult to find appropriate nonlinear functions to satisfy these assumptions in practice. Although it is difficult to show stability in theory, ADRC is also applied in many other methodology analysis and practical utility [30–32]. To the best of our knowledge, a good disturbance observer can enhance the performance of sliding mode controller, which motivates us to do this work.

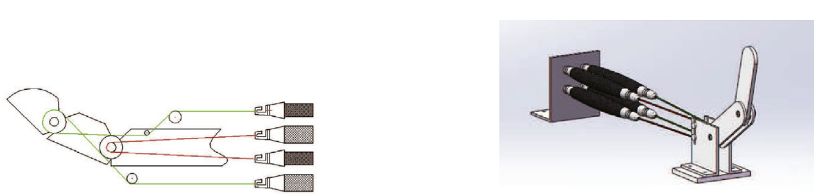
In this paper, a two-joint coupling mechanism system driven by 4 PAMs is designed. Furthermore, a nonlinear sliding mode controller based on ESO is used to deal with nonlinearities and coupling disturbances in the trajectory tracking procedure for improving the control performance of two DOF two-joint finger system. Experiment results show that the nonlinear sliding mode controller can effectively reject the disturbances and coupling nonlinearities.

The rest of this paper is organized in the following. Section 2 introduces the experiment setup and mathematical model of the two-joint dexterous hand finger system. Section 3 demonstrates the design process of ESO and SMC schematic. Experiment results and conclusion are shown in section 4 and section 5, respectively.

2. Experiment setup and dynamical model

2.1. Experiment setup

Human's fingers are driven by biological muscles of a forearm. Driven forces are transmitted by sinews, a sinew is a tough band of fibrous connective tissue that usually connect muscle to bone and it is capable of withstanding tension. Tendons are similar to ligaments, both are made of collagen. Ligaments join one bone to another bone,



(a) The diagram of dexterous hand finger. (b) The 3D model of dexterous hand finger.

Fig. 2. The Configuration of dexterous hand finger.

Please cite this article in press as: Zhao L, et al. Sliding mode control for a two-joint coupling nonlinear system based on extended state observer, ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2017.12.027