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Adaptive control for enhancing tracking performances of flexible tendon–sheath mechanism in natural orifice transluminal endoscopic surgery (NOTES)

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ABSTRACT

Tendon–sheath mechanism (TSM) has inherent advantages in the development of flexible robotic systems because of its simplicity, safety, flexibility, and ease of transmission. However, the control of TSM is challenging due to the presence of nonlinearities, namely friction, backlash-like hysteresis and the time-varying configuration of the TSM during its operations. Existing studies of TSM found in the literature only address tendon transmission under the assumption of fixed configuration and a complex inverse model of backlash is required. In order to flexibly use the system in a wider range of applications, the aforementioned nonlinear effects have to be characterized for the purpose of compensation. In this paper, we endeavor to address these issues by presenting a series of controller strategies, namely a feedforward control scheme under the assumption of known backlash-like hysteresis profile, and an adaptive control scheme to characterize the nonlinearities with unknown backlash hysteresis and uncertainties. The proposed control schemes do not require information of the tendon–sheath configurations, which is challenging to obtain in practice, in the compensation structures. In the absence of output position feedback, a simple direct inverse model-based feedforward has been used that efficiently reduce the tracking errors. The feedforward compensation does not require any complex algorithm for the inverse model. In the presence of output position feedback, a nonlinear adaptive controller has been developed to enhance the tracking performances of the TSM regardless of the random change in the tendon–sheath configurations during compensation. In addition, exact values of the model parameters are not required. They are estimated online during the operations. A dedicated experimental setup is introduced to validate the proposed control approaches. The results show that the proposed control schemes significantly improve the tracking performances for the TSM in the presence of uncertainties and time-varying configurations during the operations. There is a significant decrease of 0.0158 rad^2 (before compensation) to smaller value of 0.0012 rad^2 (use feedforward control) and 8.2815 $\times$ 10^{-5} rad^2 (use nonlinear controller) after compensation.

1. Introduction

Flexible robotic systems are often developed to operate in difficult and inaccessible environments, for example soft robotics [1], flexible snake-like robot arm [2,3], self-adaptive robot hand [4], and flexible endoscopic system [5–7]. With flexible transmission, it is easy to locate the joints away from the actuators; tendon-driven actuation is able to convey an action to a remote site via flexible tube from external actuator to the distal manipulator. It is able to transmit force/motion in very tight space, compact space, and tortuous pathways. These make this mechanism very suitable for flexible robotic systems such as UTAH/MIT hand [8], MASTER robot [9], ViaCath system [10], and DEXMART hand [11]. The tendon–sheath mechanism (TSM) is often used in flexible endoscopic systems because it is light, safe to use, flexible, and carry a high payload. Although the TSM has several advantages, nonlinearities such as friction and backlash hysteresis limits the system performances, similar to the cases presented in [12–14]. Friction and backlash hysteresis are inherent in the TSM. Control is much more challenging because these nonlinearities result in delay and inaccuracy in positioning and motion since actuators are externally located. In such cases, mathematical models and suitable control strategies can be used to mitigate the effects of nonlinearities; otherwise, performances will be limited.

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One of the earliest cable transmission model was developed by Kaneko et al. [15,16], and thereafter it was extended by Palli and Melchiorri [17,18]. Both approaches considered the tendon–sheath models as lumped-mass elements with the Coulomb or Dahl friction. They only addressed the modelling for a single TSM, disregarding the dynamic interaction between the two tendons and the two sheaths and assumed a constant tendon–sheath curvature. In addition, discontinuity still exists in the approach. However, in real applications, a pair of TSM was often used to actuate the joint in robotic arms. Using similar approaches as Palli et al., Tian et al. and Low et al. [19,20] assumed uniform pretension for all tendon elements in the lumped-mass model. The model approaches need information of the tendon–sheath configuration and discontinuity still exists when the system operates in the vicinity of zero velocity. The implementation of these models is restricted in real applications as the TSM configuration is usually unknown and difficult to measure. Another approach of modelling was introduced by Agrawal et al. [21,22], where they proposed a set of partial differential equations using a discrete tendon elements. However, it is difficult to determine whether the tendon elements are moving or stationary. In addition, this model is still limited to a fixed tendon–sheath configuration case and the curvature information must be known a priori. Recently, Do et al. [23–27] introduced new dynamic friction models for a single tendon–sheath transmission to overcome the discontinuity when the system operates at near zero velocity. However, the accumulated curve angles were assumed to be constant and no motion control schemes were introduced to compensate for the position errors.

Backlash hysteresis compensation for flexible endoscopic systems has been addressed by some researchers in the literature. There are two major approaches in these works: (i) offline-backlash hysteresis compensation without using any sensors at tool tips during the process, and (ii) online feedback using non-traditional and external sensors such as navigation systems or image processing to provide output position feedback from the distal end. Agrawal et al. [28] introduced a smooth backlash inverse model to compensate for the position errors of the tendon–sheath system. However, the followings are needed: an approximate inverse model, the backlash hysteresis profile, the bounds on the backlash parameters, and fixed tendon–sheath configuration. Do et al. [29] introduced a new backlash hysteresis model-based direct inverse control for a single TSM to enhance the tracking performance for a natural orifice transluminal endoscopic surgery (NOTES) system. But in that paper, the case is limited only to a fixed accumulated curve angle of the TSM. In addition, the information of backlash hysteresis profile is needed during the compensation. Using a similar compensation strategy in a robotic catheter system, Kesner and Howe [30,31] utilized a backlash width-based compensation approach to reduce the tracking error without considering the backlash slopes. They also indicated that the compensation of friction could not reduce the position error between the two ends. Bardou et al. [32] compensated for the backlash hysteresis in a flexible endoscope using a look-up table to predict the dead-band. Reilink et al. [33,34] and Ott et al. [35] used an image-based hysteresis reduction for the control of flexible endoscope. These approaches consider the control problems under the assumption that the nonlinear models such as backlash and hysteresis are known, the accumulated curve angles are fixed, and the feedback are available for measurement. In addition, some approaches only used the dead-band parameter for compensation regardless of the slope information for the backlash hysteresis while the others required a complex inverse model which leads to more computational cost and difficult implementation.

A search of the net, e.g. ISI Web of Science and Elsevier's Scopus, with keywords such as tendon–sheath mechanisms, tendon–sheath control, backlash compensation for tendon–sheath mechanism, and shows that compensation for a variation of the tendon–sheath configuration is not fully added. In this paper, we introduce a series of compensation controls of a pair of TSMs that comprises: (i) offline-backlash hysteresis estimation and feedforward compensation; and (ii) online adaptive compensation control for nonlinearity with uncertainties. In the case of offline-backlash hysteresis, a backlash hysteresis model based on the normalized Bouc–Wen model is reintroduced and the model parameters are estimated offline under the assumption of constant accumulated curve angles of the TSMs. The model parameters are subsequently used for a direct inverse compensation scheme-based feedforward [29]. In the case of online adaptive compensation scheme, there is no knowledge on the backlash hysteresis parameters. Uncertain phenomena are also considered to compensate for the tracking error. Adaptive update laws are designed to deal with unexpected nonlinearities like backlash hysteresis and time-varying configuration. Comparisons between the two control schemes are also presented. A dedicated experimental platform, which is used to validate the effectiveness of the proposed schemes, is developed. The results show that the proposed schemes efficiently improve the tracking performances for a pair of TSMs in the presence of uncertainties and time-varying configuration. In comparison with other approaches in the literature [21–39], our main contributions can be summarized as follow:

- In the absence of output position feedback during the compensation, our proposed feedforward control scheme does not require any complex inverse model of backlash-like hysteresis. The inverse form is directly generated from the proposed backlash-like hysteresis model. In addition, measurements of tendon–sheath configuration are not required in the compensation structure. Therefore, the proposed feedforward control scheme is beneficial for the use of tendon–sheath system in practice.
- In the presence of output position feedback, our nonlinear adaptive controller has significantly enhanced the tracking performances of the TSM regardless of random change of the tendon–sheath configurations. The exact values of model parameters are not required during the compensation. They are online estimated during the operations. In addition, the complex measurements of tendon–sheath configurations are not required and the proposed adaptive control scheme is able to deal with any disturbances and uncertainties.

The rests of this paper are organized as follow: In section 2, an overview of a pair of TSMs is presented and a direct inverse backlash hysteresis-based feedforward compensator is given. Section 3 introduces a robust adaptive control scheme which involves to unknown backlash hysteresis model, nonlinear factors, and uncertainty. A dedicated experimental setup is given in Section 4. The experimental validation and comparison are depicted in Section 5. Finally, the discussion and conclusion are presented in Section 6.

2. Problem definition and feedforward compensation

2.1. Tendon–sheath structure and its characteristics

A schematic of a pair of TSMs used in NOTES is illustrated in the upper panel of Fig. 1. It consists of a pair of TSMs with two rotation joints: the input pulley and output pulley. The lower panel of Fig. 1 shows the transmission characteristics of a pair of the TSMs.

Let x, y, and $\dot{x}$ denote the displacement at the proximal end, displacement at the distal end, and velocity at the proximal end of the system, respectively, where the pair of TSMs is routed along a