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# Real-time enhancement of tracking performances for cable-conduit mechanisms-driven flexible robots

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ABSTRACT

Natural Orifice Transluminal Endoscopic Surgery (NOTES) is a method that allows for performing complex operations via natural orifices without skin incisions. Its main tool is a flexible endoscope. Cable-conduit mechanism (CCM) or tendon-sheath Mechanism (TSM) is often used in NOTES because of its simplicity, safety in design, and easy transmission. Nonlinearities between the cable and the conduit pose challenges in the motion control of the NOTES system. It is very difficult to achieve the precise position of robotic arms when the system is inside a human's body. This paper presents new approaches to model and control a pair of CCMs (TSMs) used in NOTES system. To deal with the change of cable-conduit configurations during its operation, two control schemes are proposed: (i) an updated table with offline backlash hysteresis learning is constructed. In this case, a simple computation of the direct inverse backlash hysteresis model is introduced without using output feedback for compensation; and (ii) an online estimation of the backlash hysteresis profile under the assumption of availability of output feedback. In this case, adaptive control laws are used to deal with the change of the endoscope configuration. The proposed model and compensation control schemes are experimentally validated using a prototype of a single-DOF-Master–Slave system, which consists of a master console, a telesurgical workstation, and a slave manipulator. The results show that the proposed model and the control schemes improve the tracking performances of the system.

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## 1. Introduction

Flexible endoscope is used in minimally invasive surgery (MIS) to inspect and treat gastrointestinal (GI) tract disorders without making any abdominal incisions in the patient's body [1–3]. One of the promising surgical procedures using flexible endoscopes is the Natural Orifice Transluminal Endoscopic Surgery (NOTES). The flexible endoscope could reach potential surgical site via natural orifices or small incisions and perform flexible tasks with the attached robotic arms. A pair of cable-conduit mechanisms (CCMs) or tendon-sheath mechanisms (TSMs) is often used to actuate the robotic joints inside the human body by controlling each degree of freedom (DOF) of the robotic arms. TSM is preferred over other transmission systems because it can operate in restricted work spaces and long, narrow, and tortuous paths. Compared to other mechanisms like cable-pulley or hyper-redundant mechanism, TSM offers high payload and greater flexibility. However, the main drawbacks in the TSM are the presence of nonlinear friction and backlash hysteresis. Control of precise motion of the robotic arms is prominently a challenging issue in the use of such mechanism.

While identification methods for backlash nonlinearity are widely available in many papers (e.g. [4–8]), there are hardly any instances in the literature of a generic methodology to identify hysteresis phenomenon. Recently, various models for the TSM have been proposed and discussed to enhance performances for the TSM. Kaneko et al. [9], Palli et al. [10], Tian and Wang [11] and Low et al. [12] used lumped mass model elements to characterize the tendon-sheath transmission. Agrawal et al. [13,14] proposed a set of partial differential equations to model the tendon-sheath nonlinearity using a number of tendon elements. However, limitations still exist. Firstly, if more elements of the TSM are considered to improve the accuracy, the computation becomes more complex. Secondly, a constant pretention for all tendon elements is assumed. This is often not practical. Thirdly, the models need information of the sheath configuration along the endoscope, often difficult in practice. Lastly, discontinuous phenomena still exist in the proposed models due to the use of Coulomb friction model. Although Do et al. [15–19] introduced novel dynamic friction models to overcome the discontinuity for estimated force feedback, no motion control schemes were introduced to compensate

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for the position errors.

It is known that the backlash hysteresis profile varies with the endoscope configuration [20]. To achieve accurate tracking control, two approaches are usually used. The first requires feedback of the robotic joints be available and the second, the use of closed-loop control. Subsequently, online estimation of backlash hysteresis parameters with adaptive control laws is applied regardless of the changes of configuration. The provision of position feedback, in this case, is possible but the extra sensors at robotic joints can result in an increase in cost and a reduction in the flexibility of robotic arms (constraints in number of degrees of freedom-DOFs) as well as limit the operation space. To use this approach, a system with fewer DOFs and that works in an unrestricted space is preferred. Electromagnetic tracking system or image processing methods are potential tools to provide the output feedback [21–23]. In the case of unavailability of position feedback during the compensation, feedforward compensation is usually applied. To deal with the change of the endoscope tip, a look-up table is constructed using offline learning of backlash hysteresis parameters with respect to the endoscope configuration [20].

To improve on the tracking performances using offline learning, a backlash hysteresis model, a compensation control scheme with higher accuracy and degree of smoothness and the ease of implementations are desired. For the design of backlash compensators, Su et al. [24] and Ahmad et al. [25] indicated that the backlash model given in Tao et al. [26,27] is not suitable for system control as the backlash function is discontinuous. In the approach of tendon-sheath control, Agrawal et al. [28] used a smooth inverse of backlash hysteresis model to compensate for the position error. However, a smooth inverse model, a switching law for the velocity, and output feedback were needed. Several mathematical models of backlash hysteresis nonlinearities, such as the Bouc–Wen model, the Preisach model, the Prandtl–Ishlinskii (PI) model, were introduced [29–31]. These model structures have several shortcomings when applied to the TSM. The PI and Preisach are modeled by the sum of many elementary hysteresis namely hysterons, which increase the complexity in implementation and computation if a high number of elements is considered. The Bouc–Wen model, on the other hand, needs six parameters in its model structure to capture the hysteresis behavior. More time is needed to identify the parameters. Unlike the above models, the Dahl model [32] can capture a wide range of hysteresis and possesses simplicity with only three model parameters in its structure.

For offline learning, we develop a new approach which is based on a modification of the Dahl model to identify the nonlinear backlash hysteresis phenomena of a pair of TSMs. The new approach is simple to use for identification and in the design of a direct inverse model-based feedforward compensator to reduce the nonlinear backlash hysteresis. The direct inverse compensator does not require complex inversion of backlash hysteresis model and allows for easy implementations [33–37]. For online adaptive learning, new adaptive control laws are designed to deal with the change of endoscope configuration. In addition, the information of the bound of backlash hysteresis parameters is not required. Early works for the adaptive control schemes can be found in Tao et al. [26,27], Zhou et al. [38], Do et al. [39,40], Zhang et al. [41], Chuxiong et al. [42], and Jianping et al. [43].

In brief, two major contributions in this research include: (i) In the absence of position feedback during compensation, a new backlash hysteresis model and a simple computation of the direct inverse model-based feedforward are introduced. An updated table is constructed to deal with the change of endoscope configuration. In addition, complex inverse backlash hysteresis model with high computational cost for the compensator and discontinuous switching laws are avoided; (ii) In the presence of output position feedback during the compensation, adaptive control laws are used to enhance the tracking performances regardless of the change of endoscope configuration. Unlike the approaches of Agrawal et al. [28], Kesner et al. [44–46], Bardou et al. [20], and Do et al. [36,37], where the backlash hysteresis or the bound of parameters must be known in advance, in our schemes, their bounds are unknown and are online estimated during the compensation.

To validate the proposed approach, a dedicated single degree of freedom of a Master–Slave system is introduced. The system consists of a master console, actuator housing, and a slave manipulator. The system is similar to other NOTES systems such as MASTER [47], ViaCath [48]. Using the designed Master–Slave system, the proposed schemes are experimentally validated using real tasks such as gripping a particular object.

The paper is organized as follow: In Section 2, an overview of NOTES system and the transmission property of a pair of TSM are introduced. The design of the Master–Slave system for validation, which contains the master console, motor housing and slave manipulator, is introduced in Section 2.2. Section 2.3 presents a new approach for the backlash hysteresis model and feedforward control scheme. In addition, the development of nonlinear and adaptive control laws will be discussed in Section 2.4. Experimental compensation and comparison results are addressed in Section 3. Finally, the discussion and conclusion are drawn in

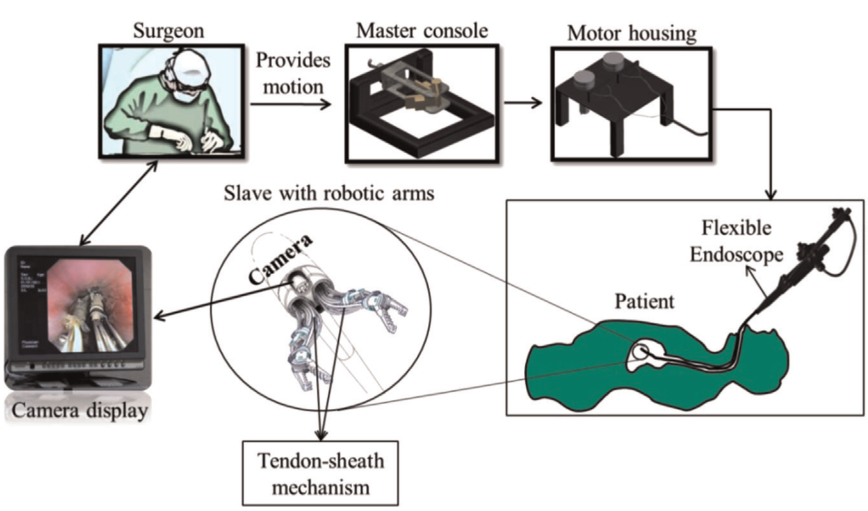


**Fig. 1.** Overview of a NOTES system.

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