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Modeling and motion compensation of a bidirectional tendon-sheath actuated system for robotic endoscopic surgery

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ABSTRACT

Recent study shows that tendon-sheath system (TSS) has great potential in the development of surgical robots for endoscopic surgery. It is able to deliver adequate power in a light-weight and compact package. And the flexibility and compliance of the tendon-sheath system make it capable of adapting to the long and winding path in the flexible endoscope. However, the main difficulties in precise control of such system fall on the nonlinearities of the system behavior and absence of necessary sensory feedback at the surgical end-effectors. Since accurate position control of the tool is a prerequisite for efficacy, safety and intuitive user-experience in robotic surgery, in this paper we propose a system modeling approach for motion compensation. Based on a bidirectional actuated system using two separate tendon-sheaths, motion transmission is firstly characterized. Two types of positional errors due to system backlash and environment loading are defined and modeled. Then a model-based feedforward compensation method is proposed for open-loop control, giving the system abilities to adjust according to changes in the transmission route configuration without any information feedback from the distal end. A dedicated experimental platform emulating a bidirectional TSS robotic system for endoscopic surgery is built for testing. Proposed positional errors are identified and verified. The performance of the proposed motion compensation is evaluated by trajectory tracking under different environment loading conditions. And the results demonstrate that accurate position control can be achieved even if the transmission route configuration is updated.

1. Introduction

Continual advancement in computer assisted tools keeps pushing the limits of what surgeons can achieve [1]. Endoscopic surgery, given therapeutic endoscopy the ability of performing complex surgical procedures, is becoming a future trend in minimally invasive surgery [2]. It involves of using a flexible endoscope as the carrier platform to access the potential surgical sites through natural orifices to obviate abdominal incision. In such a manner, many intra-abdominal surgical procedures that used to require open surgery or laparoscopic

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surgery could be performed in an even less-invasive way. This could potentially bring a series of novel surgical techniques, such as Single Port Access Surgery (SPAS) and Natural Orifice Transluminal Endoscopic Surgery (NOTES), from ethereal to tangible [3–5].

For this purpose, specific surgical robots have been developed over the past decade [6–9]. And tendon-sheath system (TSS) has found favor in such application because it allows lightweight and miniaturized design for the end-effectors; yet still, it is able to provide adequate high power transmission through the narrow, flexible transmission path along the endoscope. Recent studies have shown that the TSS is a promising candidate in delivering sufficient payload and dexterity in endoscopic surgical procedures, such as submucosal dissection [10]. A typical TSS actuated endoscopic surgical system is illustrated in Fig. 1. Distal end of the TSS connects to the end-effectors at the tip of the endoscope, body of the TSS goes through the tool-channels of the endoscope, and the actuation is externally provided by motor at proximal end of the TSS.

However, as many other minimally invasive surgical techniques, there remains a critical challenge to obtain sensory feedback from the end-effectors. In addition to the physical and medical constraints, such as limited workspace, biocompatibility and sterilizablity, it is even more technical demanding for the application of endoscopic surgery since the transmission path is narrow, flexible and even varying over time [11]. Without proper position/force information at the distal end for close-loop control, existence of any positional errors such as tendon elongation and motion backlash could significantly deteriorate the system performance. As a result, it would require surgeon to continuously adjust the inputs in order to correct the errors based on visual feedback throughout the surgery. This might impair the user experience and distract the surgeon's concentration, leading to potential prolonged operation time or safety risks. As an alternative solution, the sensory information at the distal end could be estimated by modeling the transmission characteristics of the system, such that all sensory components could be remotely located outside away from the patient with least constraints [12,13].

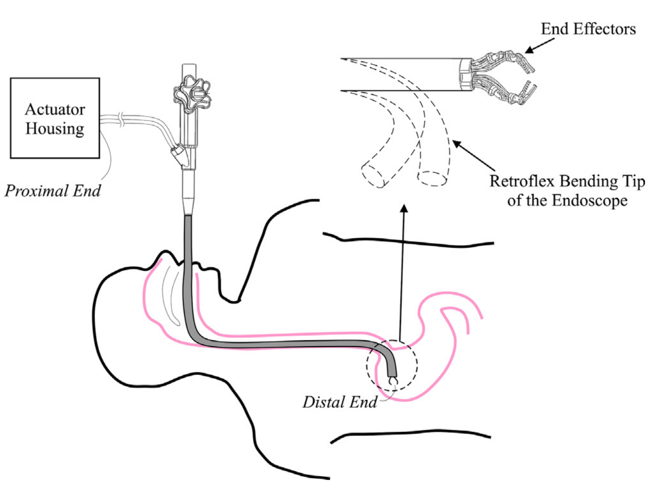

Fig. 1 – A schematic drawing of endoscopic surgery.

Modeling of the cable driven system has been intensively studied over the past decades. Many of the literature focuses on modeling the transmission characteristics of a single tendon-sheath of constant radius. Kaneko et al. modeled the tendon sheath system in the configuration of constant radius for robotic fingers [14,15]. It is concluded that the nonlinearities of the system comes from the tension-dependent friction caused by bending tendon covered by sheath. In their studies, experiments were performed on the force transmission for force control, with the assumption of tension sensors on both sides of the TSS. Following the same application, Palli et al. adopted the lumped-parameter model to study the tension transmission of a single tendon-sheath [16]. Instead of fully covered sheath, they used fixed curved supports along the pathway to form the transmission route. By installing force sensors on the curved supports, they analyzed the tension distribution along the tendon at different locations. The results show that the friction between the tendon and curved supports is the main reason for the attenuation in the tension transmission. Researches were also reported by replacing the static Coulomb friction model by more complex dynamical friction models in the modeling, such as Dahl Model [17], and Lugre Model [16,18]. But due to the complexity of the friction model, fixed transmission route of constant radius was used. Chen et al. further investigated inverse transmission modeling of the TSS, and implemented in the control of a single-tendon-sheath actuation [19,20]. They also studied the force transmission in variation conditions. It is also mentioned that the variation of actuation speed has little effect on both force and position transmission, which indicated it is reasonable to neglect the tendon inertia in the system modeling.

Aiming to extend the transmission models to arbitrary configurations, several studies have been reported recently. Phee et al. proposed a simple but effective method for calibrating the parameters of the transmission models [21]. The transmission route configuration was divided into a series of segments with different radii, but same assumption of fixed configuration was adopted. Agrawal et al. first derived the transmission model of a closed-loop cable driven revolute joint in pull-pull actuation [22]. They started modeling the TSS in continuous time-domain in the format of a set of partial differential equations (PDE); then discretized into sufficient small segments for simulation analysis. To reduce the complexity of modeling, constant radius was implemented by wrapping the tendon-sheath around a circular object. Do et al. modeled the TSS as a single element using a modified Bouc-Wen hysteresis model for position control [23,24]. The model consisted a total number of 22 parameters which were identified using genetic algorithm (GA). Thus it requires offline calibration with the assumption of fixed TSS transmission route configurations. So far, all existing works have been carried out with reference to a known fixed transmission route configuration. Little has been done on the adaptability of the modeling to configuration changes, which is important in some practical applications. For example as shown in Fig. 1, in the endoscopic surgery, a typical flexible endoscope has a bending section at the tip which can be steered in four directions up to 210°.

Previously, the authors have introduced one new parameter in the TSS transmission modeling of a single-tendon-sheath, namely the accumulated curve angle Φ. It represents