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Nonlinear friction modelling and compensation control of hysteresis phenomena for a pair of tendon-sheath actuated surgical robots

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ABSTRACT

Natural Orifice Transluminal Endoscopic Surgery (NOTES) is a special method that allows surgical operations via natural orifices like mouth, anus, and vagina, without leaving visible scars. The use of flexible tendon-sheath mechanism (TSM) is common in these systems because of its light weight in structure, flexibility, and easy transmission of power. However, nonlinear friction and backlash hysteresis pose many challenges to control of such systems; in addition, they do not provide haptic feedback to assist the surgeon in the operation of the systems. In this paper, we propose a new dynamic friction model and backlash hysteresis nonlinearity for a pair of TSM to deal with these problems. The proposed friction model, unlike current approaches in the literature, is smooth and able to capture the force at near zero velocity when the system is stationary or operates at small motion. This model can be used to estimate the friction force for haptic feedback purpose. To improve the system tracking performances, a backlash hysteresis model will be introduced, which can be used in a feedforward controller scheme. The controller involves a simple computation of the inverse hysteresis model. The proposed models are configuration independent and able to capture the nonlinearities for arbitrary tendon-sheath shapes. A representative experimental setup is used to validate the proposed models and to demonstrate the improvement in position tracking accuracy and the possibility of providing desired force information at the distal end of a pair of TSM slave manipulator for haptic feedback to the surgeons.

1. Introduction

Natural Orifice Transluminal Endoscopic Surgery (NOTES) has found great use amongst the surgical communities. It can be used to access the peritoneal cavity without making any abdominal incisions and in complex surgical tasks such as in intracorporeal suturing. Its benefits include a reduction of trauma, healing time, and of lost blood, enhancement of better cosmetic and faster recovery for the patients [1–3]. A typical illustration of NOTES procedure is shown in Fig. 1. Surgeons perform the surgical tasks using a master console to control the robotic arms inside the patient's body. One of the main tools of NOTES is a long and flexible endoscope often used in gastroenterology. It is a flexible shaft with an articulated bending tip and tool channels to house the robotic arms. A camera is attached to the end of the endoscope to provide visual feedback to

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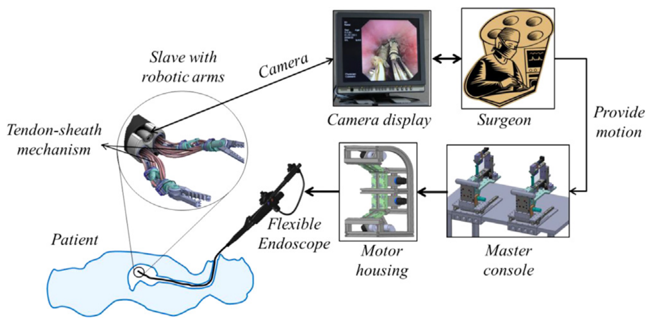

Fig. 1. Illustration of a Natural Orifice Transluminal Endoscopic System (NOTES).

the surgeon. The robotic arms with multi degrees of freedom (DOFs) are fixed and carried along with the endoscope to perform demanding surgical procedures such as suturing and cutting. Triangulation is carried out at the distal end of the endoscope while actuation is externally provided.

To actuate the robotic arms in the flexible endoscopic systems, tendon-sheath mechanism (TSM) is used. This mechanism consists of a hollow helical coil wire and an internal cable; it can pass through long narrow and tortuous paths allowing it to operate in small working areas. This allows for a drastic reduction of the system size and increases flexibility. In addition, it does not require high electrical power or actuator at the distal end to operate the slaved tools. Because of the constraints in size and the requirements for sterilization of any tools inside the body, traditional sensors cannot be placed at the end effectors. Therefore, only open-loop controllers are used. In TSM, nonlinearities such as friction and backlash hysteresis cause major challenges in controlling the precise motion of the robotic arms and providing haptic feedback to the surgeons. It was reported that haptic feedback to the surgeon will be essential for safe surgery [4–6]. Without haptic feedback, surgeons cannot have the same feeling as they have with direct contact and handling of the tissues. As sensors are not available at distal end of the system, mathematical models can be used as potential substitutes. We develop and propose the use of two transmission models of the flexible TSM to accurately estimate the force and position data at the distal end to assist in the operations of the surgical robotic arms.

Various analytical model parameters of friction and motion for a single TSM using lumped mass model combined with Coulomb friction or Dahl model have been proposed. Kaneko et al. [7,8] introduced a tendon-sheath model using lumped mass and Coulomb friction model. Palli and Melchiorri [9,10], Tian and Wang [11], Chen and Wang.[12] and Low et.al [13] modelled the transmission of a single TSM under the assumption of the same pretension for small elements. Agrawal et al. [14,15] used a set of partial differential equations to model a single TSM and a pair of TSM in a closed loop approach. Existing approaches only consider the transmission model for a single TSM when the configuration is known. It becomes more complex when more tendon elements are considered. In addition, they utilize the Coulomb friction model which has a discontinuity when the system operates near zero velocity (reversal motion or stationary state). These approaches are impractical because the sheath curvatures are often unknown during the operation and because they could not provide force information when the system operates near zero velocity i.e. at the onset of motion. Although Agrawal et al.[16] used a smooth backlash inverse model to compensate for the errors, they still need output feedback for online estimation of the model parameters. For a robotic catheter system, Kesner and Howe [17,18] implemented a backlash width-based compensation method to improve the tracking performances without considering backlash slopes. Bardou et al. [19] compensated for the backlash hysteresis in a flexible endoscope using a look-up table to estimate the dead-band. However, these approaches only consider the control problems under the assumption of the presence of feedbacks from the tool tips. There are still discontinuities when system operates near zero velocity. In practice, this assumption of the availability feedback is not valid for most surgical robots in current usage.

For the TSM, the friction force characteristics is rather complex. The forces are different when the motion is accelerating or decelerating. The current friction models like Dahl, LuGre, Leuven, or GMS [20–24] are not able to describe the complete TSM friction characteristics as they mainly characterize the friction force with the same values for both acceleration and deceleration phases. It was known that the normalized Bouc–Wen model can describe a wide class of hysteresis systems [25,26]. It has been applied in many systems, such as in structure element analysis and magnetorheological systems, to represent the hysteresis inherence in such engineering problems. Hence, here we will develop an asymmetric friction model using the modified normalized Bouc–Wen model to capture the nonlinear behavior of friction for a pair of TSM. The goal is to use this modified model to estimate the friction force to provide feedback to the haptic devices.

To enhance the position tracking performances, a backlash hysteresis model is needed. Although several mathematical models of backlash hysteresis nonlinearities including the Bouc–Wen model, Preisach model, Prandtl-Ishlinskii (PI) model were introduced and discussed in Macki et al. [27] and Hassani et al. [28], and some identification methods for the nonlinearity are widely discussed (e.g. [29,30]), there are several shortcomings in these model structures for tendon-sheath applications. The PI and Preisach are modelled by the sum of many elementary hysteresis namely hysterons, which increases the complexity in implementation and computation if a high number of elements is considered; and the Bouc–Wen model needs a high number of model parameters to capture hysteresis, i.e. more than five parameters. Unlike the above models,