Nonlinear Modeling and Parameter Identification of Dynamic Friction Model in Tendon Sheath for Flexible Endoscopic Systems

T. N. Do[1], T. Tjahjowidodo[1], M. W. S. Lau[2] and S. J. Phee[1]
[1]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Robotic Research Centre, 50 Nanyang Avenue, Singapore, 639798, Singapore
[2]School of Mechanical and Systems Engineering, Newcastle University International Singapore (NUIS), 180 Ang Mo Kio, Avenue 8, Block P, Room 220, Singapore, 569830, Singapore
thanh4@e.ntu.edu.sg, ttegoeh@ntu.edu.sg, michael.lau@newcastle.ac.uk, msjphee@ntu.edu.sg

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Abstract: Minimally Invasive Surgery (MIS) has established a revolution in surgical communities, with its many advantages over open surgery. The need of more simplicity and high maneuverability makes the tendon sheath a very suitable mechanism in flexible endoscopic systems. Due to the restriction on size constraints and sterilization problems, traditional sensors cannot be mounted on the tool tips of a slave manipulator. Moreover, in the presence of nonlinear friction and hysteresis between the tendon and the sheath, it is extremely difficult to control the precise motion and sense the force during the operation. This paper proposes a new dynamic friction model to estimate the force at the end effector for the tendon sheath mechanism. The proposed friction model can adapt with any initial pretension of the tendon and any configuration of the sheath. The nonlinearities in both sliding and presliding regimes can be captured by using an internal state variable and functions dependent velocity and acceleration. A specific setup has been designed in order to measure the friction force between the tendon and the sheath. Finally, the validity of the identified model is confirmed by a good agreement of its prediction and experimental data.

1 INTRODUCTION

The introduction of robotic assistance for minimally invasive surgery (MIS) opened a revolution in surgical communities during the past few years, with the advantages to perform complex surgical tasks such as intracorporeal suturing. MIS has many benefits such as a reduction of trauma and healing time, reduction of lost blood, enhancement of better cosmetic and faster recovery for the patients (Nagahiro et al., 2001; Förster et al., 2002; Bodner et al., 2004). Natural Orifice Transluminal Endoscopic Surgery (NOTES) is an emerging surgical technology that accesses the peritoneal cavity without any abdominal incisions. In a laparoscopic surgery, surgeons directly use their hand to operate surgical instrument. However, in laparoscopic surgery using robots, surgeons perform the surgical tasks using a master console to control a slave manipulator inside the patients as in Figure 1.

To actuate the slave manipulator in flexible endoscopic systems, tendon sheath mechanism is preferred. This type of mechanism consists of a hollow helical coil wire and an internal cable (Phee et al., 2010). The tendon-sheath system can pass through a long narrow and tortuous path, meaning that it can operate in small working areas, and allows for a drastic reduction of system size. Moreover, it does not require high electrical power or actuator at distal end to operate the slave. The need of flexible actuation such as low bulkiness, high maneuverability and degrees of freedom, small in size, light weight, cheaper and simpler design, and safety on human body, have made the tendon-sheath a very suitable mode for transmission. Due to the size constraints and sterilization problems, traditional sensors cannot be mounted at end effectors. Moreover, nonlinearities in the tendon sheath cause major challenges not only in modelling but also in enhancing system performances. In order to enable surgeons to feel as they have in direct touch on the tissue, several activities proposed the model parameters for tendon sheath in terms of analyses of lumped mass model combined with Coulomb friction or Dahl model (Dahl, 1968), in which a set of algorithms provides an estimation for force at end effectors.

Kaneko and his colleagues (Kaneko et al., 1991) analytically modelled tendon sheath in terms of small elements, in which apparent tendon stiffness was combined with lumped model parameters and Coulomb friction to estimate the tendon tension along the sheath. Similar approach was proposed by researchers at University of Bologna (Palli and Melchiorri, 2006; Palli et al., 2009; Palli et al., 2012). They replaced Coulomb friction model by Karnopp and Dahl friction models to characterize nonlinear hysteresis in the tendon sheath. However, their approaches are only based on the assumption of constant pretension tendon and sheath curvature for each lumped element. Later, Agrawal and Bin (Agrawal et al., 2008; Agrawal et al., 2010) used a set of partial differential equations to predict the load transmission of the tendon sheath with any pretension and the sheath curvature. However, it is too complicated when the sheath shape in terms of helical or spatial types. Moreover, in the case of static friction model, like Coulomb, it is extremely lost the force information when the tendon is in stationary state.

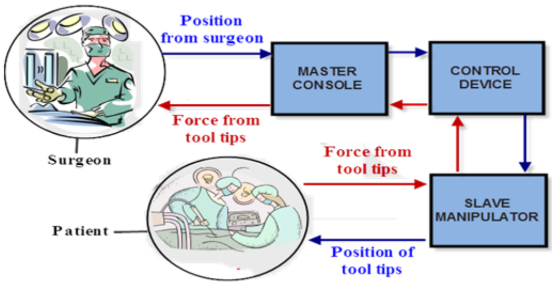


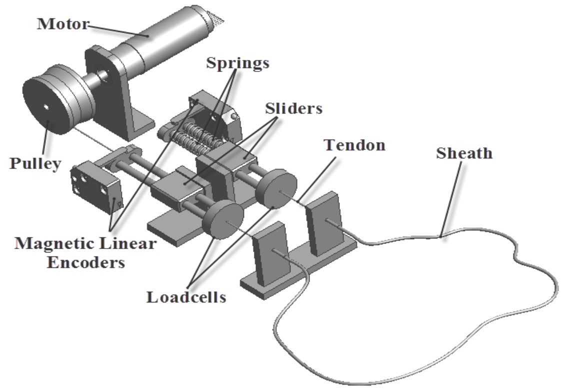
Figure 1: Overview of a surgical system.

Unlike existing approaches in the literature, a dynamic friction model that we propose in this paper is based nonlinear hysteresis friction in relations with acceleration and velocity, and under several assumptions such as fixed sheath shape, no slack of the tendon. It considers the tendon sheath as one element and is able to capture well hysteresis force for both sliding and presliding regimes. It has been shown that when the tendon sheath is moving at small displacement and slow velocity, the proposed model can predict exactly the force transmission in the system. This is not available on the current approaches. The proposed model is subsequently validated through experiments and suitable identification technique. The limitation of the proposed model in applying the force feedback and position control will be discussed at the end of this paper.

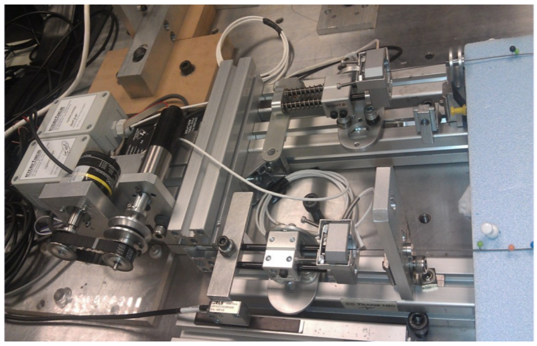
2 EXPERIMENTAL WORK

2.1 Experimental Setup

In order to observe the friction phenomena between the tendon and the sheath, an experiment setup has been conducted as shown in Figure 2. For a flexible endoscopic system using tendon sheath mechanism, the slave manipulator is actuated by a cable passing through a sheath. The nonlinearities occur in the motion cause tension losses. If the higher pretension is applied, the slack can be avoided but causes higher friction force. In contrast, the lower pretension leads to slower friction force but causes tendon slacking. Therefore, in this experiment, we applied a suitable pretention for the tendon in order to avoid the tendon slacking.



a) Schematic of the setup.



b) A general view of the real setup.

Figure 2: Experimental setup.

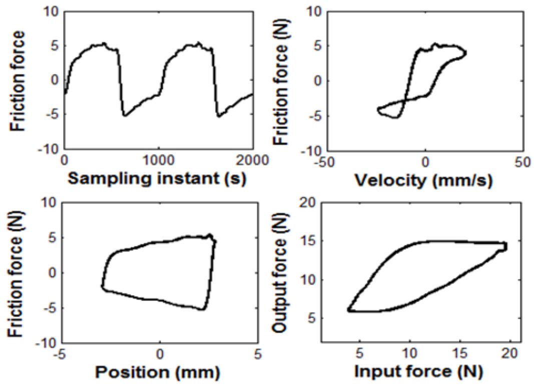
The system is actuated by a Faulhaber 2642W024CR DC servomotor with a gearhead with ratio of 134:1 via a pulley and a cable. Two load cells LW-1020-50 from Interface Corporation are utilized to measure the tendon tension at two ends of the tendon sheath. In order to maintain the bidirectional motion between tendon and sheath, two linear springs are used at distal ends of the system. The main purpose of using two springs is to simulate the force at end effector and to create a suitable initial pretension for the tendon. To hold the load cells, two linear sliders are used, which are free to move in space as well as to serve as platforms for guiding two linear springs to slide. Two magnetic linear encoders LM15 with high resolution of 5µm from RLS d.o.o are also used. One is mounted at the proximal end to provide the position and velocity information for the input signal and motor control, while the other is attached at the end effector to measure its position and velocity. In the middle, a tendon and sheath are assembled for transmitting forces from the proximal end to the end effector. The tendon from Asahi Intecc Co. with the size of WR7x7OD0.27mm Teflon coated wire ropes outside is used. The sheath is round-wire coil, also from Asahi Intecc Co., with inner diameter of 0.36 mm and outer diameter of 0.8 mm. Both, the tendon and the sheath are fixed in the platform, which can free to regulate the sheath shape. The motor is driven by using ADVANCED motion controls 25A8PWM servo drive, while each load cell is connected with a DCA compatible signal conditioner from Interface. The whole system is controlled by a simple PID controller in combination with MATLAB Simulink tool from MathWorks, Inc. and a dSPACE DS 1104 controller board from dSPACE Inc. During the measurements, various displacement excitations are provided by the motor and controllers to the system. Different frequencies and amplitudes of sinusoidal excitations are also applied to capture the behaviours of tendon sheath friction during the experiments.

2.2 Experimental Results

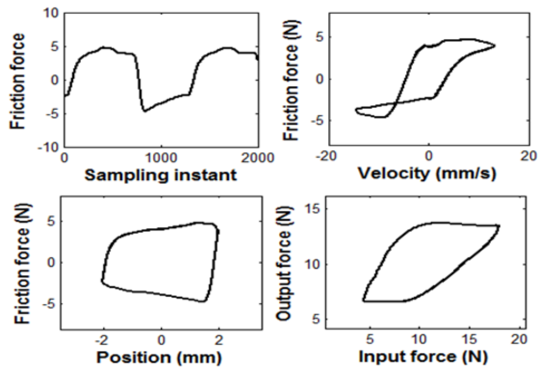
In general, a tendon sheath mechanism can be viewed as an element with one input: displacement (or velocity), and one output: displacement (or velocity). The force balance for the tendon sheath as one element can be written as:

$$T_{in} + T_{out} + F = 0 \tag{1}$$

where T_{in} is the tension input from master console, T_{out} is the tension output at end effector, F is the friction force occurring when the tendon slides on the sheath. The tension input T_{in} and output T_{out} can be measured by two load cells. Then the friction force F can be obtained by Eq. (1). The position input (x) is measured using the magnetic linear encoder LM15. The experimental results have been obtained using two sinusoidal signals at the input side, i.e. 1hz and 0.8hz, and are shown in Figure 3.



a) Experimental results with an input sinusoidal signal of 1hz.



b) Experimental results with an input sinusoidal signal of 0.8hz.

Figure 3: Experimental results.

3 TENDON SHEATH SYSTEM AND FRICTION MODELLING

The friction force F in Eq. (1) is our main concern. Responding to the problems of tendon sheath as in above experimental results, a novel dynamic friction model for tendon-sheath is proposed here.

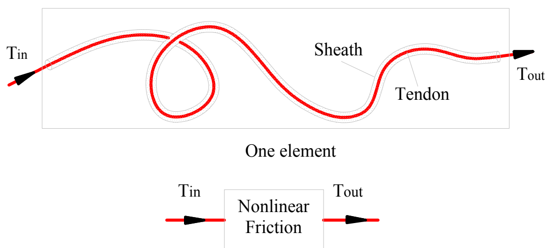


Figure 4: Model of tendon sheath with one element.

The model considers the system as a single degree of freedom (SDOF) system (Figure 4) with an advanced asymmetric friction model to capture the unique hysteresis loss in the tendon-sheath system based on the Dahl friction model (Dahl, 1968). A single tendon and a sheath are considered in this case.

3.1 Asymmetric Hysteresis Friction Model in Sliding Regime

The main model contains four components corresponding to acceleration and deceleration. Current approaches on the friction models are only based on position and velocity information (Armstrong-Hélouvry et al., 1994; Canudas de Wit et al., 1995; Al-Bender et al., 2005). Wojewoda and his colleagues (Wojewoda et al., 2008) used acceleration information to capture hysteresis loops for both acceleration and deceleration parts. Motivated by this approach, a set of functions dependent velocity and acceleration will be formulated in this paper. At steady state, i.e. $\dot{\zeta}(t)=0$, the friction force $F_f(\dot{x},\ddot{x})$ will be represented by:

$$F_f(\dot{x},\ddot{x}) = \begin{cases} G_{anvp}(\dot{x},\ddot{x}) & \text{if } \ddot{x}\le 0, \dot{x}\ge 0 \quad (2a) \\ G_{anvp}(\dot{x},\ddot{x}) & \text{if } \ddot{x}\ge 0, \dot{x}\ge 0 \quad (2b) \\ G_{anvn}(\dot{x},\ddot{x}) & \text{if } \ddot{x}\le 0, \dot{x}\le 0 \quad (2c) \\ G_{anvn}(\dot{x},\ddot{x}) & \text{if } \ddot{x}\ge 0, \dot{x}\le 0 \quad (2d) \end{cases}$$

where $x,\dot{x},\ddot{x}$ denote the position input, velocity input, and acceleration input, respectively.

$$\circ\; G_{anvp}(\dot{x},\ddot{x}) = \rho_1 + \mu_1 e^{-f_1(\dot{x},\ddot{x})}$$

$$\text{with } f_1(\dot{x},\ddot{x}) = \frac{\kappa_1|\dot{x}|}{|\kappa_2\ddot{x}|+1}$$

$$\circ\; G_{apvp}(\dot{x},\ddot{x}) = \rho_1 + \mu_1 e^{-f_1(\dot{x},\ddot{x})} + \mu_2\left(1\text{-}e^{-|\kappa_3\ddot{x}|}\right)$$

$$\circ\; G_{anvn}(\dot{x},\ddot{x}) = \rho_2 + \mu_3 e^{-f_2(\dot{x},\ddot{x})}$$

$$\text{with } f_2(\dot{x},\ddot{x}) = \frac{\kappa_4|\dot{x}|}{|\ddot{x}|+\kappa_5}$$

$$\circ\; G_{apvn}(\dot{x},\ddot{x}) = \rho_2 - \mu_3 e^{-f_2(\dot{x},\ddot{x})}$$

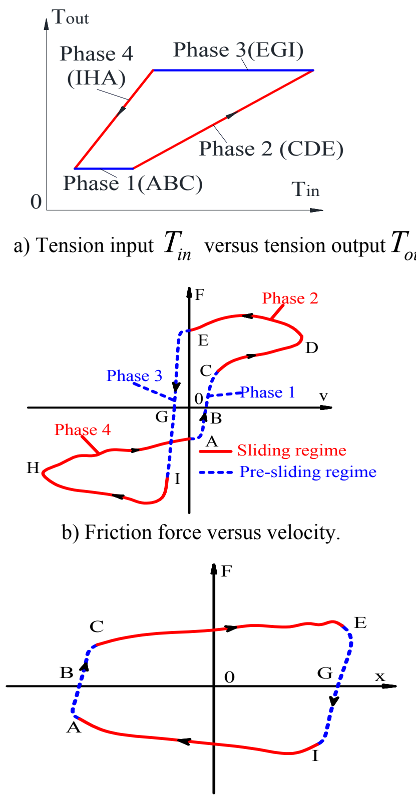
The coefficients $\mu_1,\mu_2,\mu_3,\rho_1,\rho_2$ and $\kappa_1,\kappa_2,\kappa_3,\kappa_4,\kappa_5$ are constants that control hysteresis loops in the sliding regime. The subscript letters *a, n, v, p* refer to acceleration, negative direction, velocity, positive direction, respectively.

3.2 A New Dynamic Friction Model for both Sliding and Presliding Regimes

Dahl (Dahl, 1968) formulated a new friction model that can capture hysteresis in presliding regime by introducing an internal state $\zeta(t)$. In a survey of friction model (Armstrong-Hélouvry et al., 1994), a simple form for the Dahl model was made by:

$$\dot{\zeta}(t) = \dot{x}(t) - \sigma\frac{|\dot{x}(t)|}{F_c}\zeta(t) \qquad (3)$$

where F_c is a Coulomb friction force, σ is bristle stiffness. At steady state, the normalized friction force $\zeta(t)=F_c$. From this special property, we observed that we can replace the constant force F_c by the force in sliding regime $F_f(\dot{x},\ddot{x})$ given by Eq. (2a-2d).



a) Tension input T_{in} versus tension output T_{out}.

b) Friction force versus velocity.

c) Friction force versus position.

Figure 5: Nonlinear characteristics of friction between tendon and sheath.

The friction force in the sliding regime and the Dahl model are included in a unique new model that can describe nonlinear hysteresis in tendon sheath. Theproposed model can be given by:

$$\dot{\zeta}(t) = \dot{x}(t) - \sigma \frac{|\dot{x}(t)|}{F_f(\dot{x}, \ddot{x})} \zeta(t) \quad (4)$$

$$F(t) = \sigma \zeta(t) \quad (5)$$

Referring back to Figure 5, along the curve AB, the friction force is in the pre-sliding regime and its values are represented by a combination of the dimensionless value $\zeta(t)$ and the stiffness σ. This curve conresponds to Phase 1. At steady state, i.e. $\dot{\zeta}(t) = 0$, the friction force at sliding regime $F(t) = F_f(\dot{x}, \ddot{x})$, the curves CD and DE corespond to the acceleration and deceleration directions. This curve is in the Phase 2 on the right figure. The same arguments hold for Phase 3 and Phase 4 corresponding to the curves EGI and IHA. A spectial property of the proposed model is that the transition from presliding to sliding regime is guaranteed to be smooth. Moreover, the proposed model captures well the force when the system is at zero velocity (Phase 1 and Phase 3).

4 PARAMETER IDENTIFICATION OF THE PROPOSED FRICTION MODEL

To validate the proposed friction model, the identification experiment was carried out by applying a sinusoidal input signal in experimental setup. Parameters of the proposed model are firstly identified by applying a genetic algorithm (GA) (Mitchell, 1996) to generate a initial guess of the parameters. Subsequently, after having a rough estimation, the obtained parameters are used as an initial guess in the Nelder-Mead Simplex Method to refine the result. The whole processes are carried out by MATLAB Identification Toolbox from MathWorks. As a measure of performance, the mean square error (MSE) was used and defined by:

$$\mathrm{MSE}(\hat{F}) = \frac{1}{N}\sum_{i=1}^{N}\left(F - \hat{F}\right)^2 \quad (6)$$

where F is the output (the force values are measured from the experiment).

For the identification of the friction force in tendon sheath, 11 parameters have to be identified. Figure 6 depicts the results of the identification consisting 11 parameters for a sinusoidal input signal 1 Hz of both sliding and presliding regimes. The 11 parameter values are shown in Table 1.

Table 1: Identification result for the proposed model.

$\rho_1 = 2.097$	$\rho_2 = 3.960$
$\mu_1 = 1.368$	$\mu_3 = -1.855$
$\kappa_1 = 0.172$	$\kappa_4 = 5.549$
$\kappa_2 = 1.228$	$\kappa_5 = 0.005$
$\mu_2 = 1.579$	$\sigma = 17.57$
$\kappa_3 = 0.016$	

The upper left panel of Figure 6 shows the actual friction force (dashed line), friction model (solid line), and the error for both results. The upper right panel shows the proposed model and actual force versus velocity, while the lower panel depicts the friction force of the real data and proposed model in relation with position.

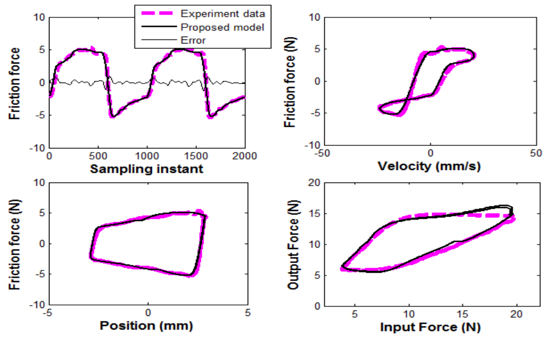


Figure 6: Identification results compared between the proposed model and experiment data (for1hz).

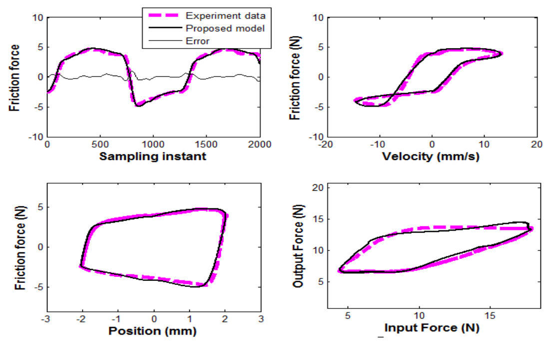


Figure 7: Identification results compared between the proposed model and experiment data (for 0.8hz).

The same results are represented for a sinusoidal input signal of 0.8 Hz and are shown in Figure 7. The parameter values in Table 1 are also used in this case. The proposed model offers the better estimation results compared to the current approach utilizing lumped mass model. This means that this model offers a major advantage of capturing friction force at area near zero velocity, i.e. when the system stops, and guarantees a smooth transition from presling to sliding regimes. Moreover, at small displacement, the friction force changes very rapidly. The proposed model can track quite well in this case as shown in Figure 6 and 7.

5 CONCLUSIONS

This paper has introduced a new dynamic friction model to solve the haptic feedback problems for flexible endoscopic system using tendon sheath mechanism. The proposed model incorporates acceleration and velocity information in the sliding regime and uses a modification of the Dahl dynamic friction model to capture the hysteresis for both presliding and sliding regimes. The new model can give a smooth transition between the two regimes (sliding and presliding regimes) and is capable of prediction friction near zero velocity.

Validation experiments have been carried out to evaluate the proposed model. An efficient identification method (Genetic Algorithm) has firstly used to generate a rough initial guess of model parameters. The obtained results have been refined using the Nelder-Mead Simplex Method. The comparisons between the proposed model and the experiment data have shown a good agreement for the approach. It can be concluded that the proposed model promises an efficient approach not only in accurately predicting the force for haptic feedback but also in any surgical devices that have similar friction characteristics as the tendon sheath.

Future activities will be conducted by developing the experimental setup for a pair of tendon sheath and the proposed model to adapt to any configuration of the sheath. A hysteresis compensation for both position and friction force feedback will be also developed using suitable nonlinear control schemes and taking into consideration for higher degrees of freedom in the system.

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