Friction Compensation for a Force-Feedback Teleoperator with Compliant Transmission

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Abstract—Friction forces in the joints of manipulators of a force-feedback teleoperator apply unwanted resistant forces to the human operator who moves the master manipulator. The resistant forces contribute to operator fatigue and reduce the transparency of the teleoperator in low frequencies. This paper presents a model-based approach to cancel friction in manipulators of a teleoperator with a compliant tendon drive. Friction compensation reduces the resistant forces applied to the operator and improves the transparency, but it can cause oscillations. This is due to displacement lags between the inputs to the friction compensators and actual displacements of friction contact surfaces that can cause overcompensation around zero velocity. We use a low-stiffness Dahl model to prevent overcompensation around zero velocity. It is shown using passivity theory that the low-stiffness friction compensators preserve the passivity of the teleoperator. Experiments performed on a teleoperator confirm the theoretical results.

I. INTRODUCTION

Friction limits the performance of a force-feedback teleoperator. A teleoperator consists of a master manipulator, a slave manipulator, and a controller that virtually connects the two manipulators. When an operator moves the master manipulator to direct the slave manipulator to perform a task, friction in the joints of the manipulators resists the operator's motion. The resistant friction forces contribute to the operator's fatigue and mask small forces of the teleoperated environment.

A position-tracking controller is often used to generate force feedback to the human operator of a teleoperator. The tracking controller commands the master manipulator to follow the slave manipulator. The controller applies force to the operator when the master manipulator is displaced from its desired position. The applied forces consist of the friction forces of the manipulators, the inertial forces of the manipulators, the forces of the controller, and the reflected forces from the teleoperated environment. The friction forces and internal forces applied to the operator can be scaled down by adding a force control loop to the controller, but this requires using force sensors. The use of force sensors is significantly limited in certain teleoperators due to practical considerations [1].

Alternatively, friction forces of a teleoperator can be canceled by model-based friction compensators that are integrated into the position-tracking controller. This requires

friction models that accurately calculate friction forces and do not destabilize the teleoperator.

Friction occurs in a tendon-drive joint of a manipulator at several stages of power transmission. It occurs in the actuator that moves the tendon, the joint of the manipulator driven by the tendon, and the pulleys that support the tendon. Since the tendon is stretched during force transmission, the displacements of the friction surfaces of tendon mechanism are slightly different from the displacement input to the controller. These slight displacement lags can cause oscillations when a model-based compensator is used to cancel friction. For example, consider a friction compensator used to cancel friction forces in a tendon-drive gripper. Friction occurs both in the joint of the gripper and in the joint of the actuator. The friction compensator causes the tendon and the actuator to oscillate when the transmitted force through the tendon is not enough to move the gripper and the generated energy by the compensator is more than the energy dissipated in the joint of the actuator.

In this paper, we develop a friction compensator that compensates friction in the joints of a tendon-drive manipulator up to a level that does not cause oscillations. The friction forces in the joints are evaluated by a compensation model that does not overestimate dissipated energy in the joints of the tendon mechanism despite of a displacement lag of the tendon mechanism. The friction compensator prevents the friction forces of the tendon mechanism from being transmitted to the human operator of the teleoperator for any system state, except when the friction compensator is in a transient displacement state around zero velocity.

The rest of this paper is organized as follows: Section II reviews related work. Section III explains the control objectives for a teleoperator. Section IV presents a friction model for a tendon-drive joint. Section V introduces a low-stiffness friction model to compensate friction in a tendon-drive joint. Section VI analyzes the stability of the friction compensation using passivity theory. Section VII discusses the experimental results. Section VIII concludes the paper.

II. RELATED WORK

Armstrong et al. [2] and Olsson et al. [3] surveyed various friction compensation techniques and friction models used for minimizing position tracking errors of control systems.

Fig. 1. A teleoperator consists of a master manipulator, a slave manipulator and a position tracking controller. The controller can be considered as a virtual spring that connects the tips of the manipulators.

Model-based friction compensators [4], observer-based compensators [3], [5], [6], and non-model-based controllers [7] are used to reduce position tracking errors of systems with friction. In this paper, we use a model-based friction compensator to reduce force tracking errors of a teleoperator.

Passivity theory has been used to prove the stability of tracking control systems with observer-based friction compensators that applied LuGre (Lund Grenoble) models [3], [6]. The overall tracking control system consists of the connection of two passive subsystems. One subsystem describes the tracking controller and the other the friction compensator. The passivity of both subsystems together guarantees global asymptotic position tracking.

Friction compensation has been used for haptic displays. In [8], a hybrid compensation method was applied to compensate friction in a haptic display. The hybrid compensator combined a model-based feedforward compensator and force feedback to cancel friction. In [9], a friction model was constructed off-line through a machine learning method. The friction model then was used for online feedforward compensation of friction in a haptic display. These compensation approaches may not guarantee robust stability for a tendon-drive telerobotic system.

Friction compensation has been studied for flexible mechanisms [10], [11], [12]. Townsend and Salisbury [11] used the describing function technique to investigate friction-generated limit cycles in a force control. Olsson and Astrom [10] analyzed friction-generated limit cycles in a flexible servo system by generalizing an analytical method used in relay-feedback systems. Hayward and Cruz-Hernandez [12] used a feedforward friction compensation method based on a Wiener model to cancel friction in a tendon-driven joint. The feedforward compensation accurately cancels friction for a narrow range of load change. In [13], we used a Dahl model to compensate friction in the joints of a teleoperator. In this paper, we extend our previous work to prove that a low-stiffness Dahl model provides passive friction compensation for a teleoperator with compliant tendons. The low-stiffness Dahl model preserves the passivity of the joint under all possible trajectories, but it may not estimate friction in a tendon-driven joint as accurately as the Elasto-Plastic friction model does [14].

III. CONTROL OBJECTIVES FOR A TELEOPERATOR

A teleoperator with a position-tracking controller is shown in Figure 1. The controller receives the position of the master

Fig. 2. Friction in joints of a tendon-drive system. (a) The tendon-drive system. (b) Friction in the joints can be visualized as contact through elastic bristles.

manipulator and sends power commands to the slave manipulator to follow the master position. In a force-feedback teleoperator, the controller also provides power commands to the actuators of the master manipulator in order to apply desired resistant forces to the operator.

The control objectives for a force-feedback teleoperator include [15]:

- *Position tracking*: the slave manipulator should follow the position of the master manipulator.
- *Transparency*: the master manipulator should reflect the impedance of the remote environment to the operator.

Friction in the joints of a teleoperator opposes the above control objectives. Friction significantly decreases the transparency of the teleoperator where the friction forces are on the scale of the environment forces. When there is no force control loop, the teleoperator acts like an open loop system, which is not robust to disturbances such as those caused by friction. In Section V, we use a model-based friction compensator to cancel friction in a teleoperator to increase transparency.

Friction in the joint of the slave manipulator of a teleoperator affects tracking accuracy. When the controller forces are less than the friction forces, the controller is not able to move the slave manipulator to the desired position. The slave manipulator follows the master manipulator position with a small tracking error. However, for a teleoperator in which the human operator relies on visual feedback to control the position of the slave manipulator (such as teleoperators used in minimally invasive surgery), small position errors caused due to friction might be ignorable.

IV. FRICTION IN A TENDON-DRIVE MANIPULATOR

Figure 2a shows a tendon-drive system for controlling a joint of a manipulator. The system consists of an actuator, a joint near the tip of the manipulator, and a tendon that transmits power from the actuator to the tip. The position of the actuator is measured by an encoder attached to the

Fig. 3. Model-based friction compensation for a tendon-drive system.

actuator. x represents the linear displacement caused by the actuator and f_{input} is the force generated by the actuator. The friction contacts mainly take place in the actuator joint and the tip joint. $f_{\text{friction1}}$ represents friction force in the actuator joint and $f_{\text{friction2}}$ represents friction force in the tip joint. $f_{\text{friction1}}$ can be estimated from the displacement of the actuator measured by an encoder. $f_{\text{friction2}}$ can be estimated from the displacement of the tip joint, which is not measured. The net friction force in the input to the actuator is calculated by:

$$f_{\text{friction}} = f_{\text{friction1}} + f_{\text{friction2}}. \quad (1)$$

Friction in the joints arises due to contact of the asperities of the joint surfaces. This can be visualized as rigid surfaces that make contact through elastic bristles [4] (Figure 2b). The tendon can be modeled by a spring that connects two sets of bristles located at each end of the tendon. When the actuator force is gradually increased, the bristles on the actuator side of the tendon start to deflect. Bristles with large deflections slip. When the actuator continues to move, the bristles at the tip joint are deflected and the tendon is stretched. The deflection spectrum of the bristles is random, but an average can be used to estimate friction forces. The average deflection can be estimated from the displacement of each rigid surface by a LuGre model or a Dahl model [4], [16].

However, in this paper first we use Coulomb models to represent friction in the actuator joint and tip joint:

$$\begin{aligned} f_{\text{friction1}} &= f_{C1} \text{sgn}(v_1) \\ f_{\text{friction2}} &= f_{C2} \text{sgn}(v_2) \end{aligned} \quad (2)$$

where v_1 and v_2 are the velocities of the actuator and the tip and f_{C1} and f_{C2} are the Coulomb force levels. Since the compliance of the tendon is much larger than that of the bristles, we use Coulomb model to represent friction in the joints.

V. MODEL-BASED FRICTION COMPENSATION

To compensate friction in a tendon-drive system of a joint of a position-tracking teleoperator, a friction compensator is integrated into the controller of the teleoperator for that joint (Figure 3). The output of the compensator is subtracted from the output of the controller, and then it is applied to the input of the actuator of that joint:

$$f_{\text{input}} = f_{\text{controller}} - f_{\text{comp}}. \quad (3)$$

The compensator estimates the friction in the tendon-drive system. Since the position of the tip joint is not directly

Fig. 4. Passive friction compensation.

available to the system, the compensator estimates the friction forces from the displacement of the actuator alone.

Considering the bristle description of Figure 2b, we extract a conservative model to estimate friction that does not overestimate the friction-dissipated energy of the tendon-drive system. First, we integrate the tendon stiffness into the stiffness of the bristles located at the tip. This results in low-stiffness bristles that are directly connected to the actuator. Then we replace the bristles in the actuator joint by similar low-stiffness bristles. Finally, a first order Dahl model is used to estimate the forces of the bristles:

$$\frac{df_{\text{comp}}}{dx} = \sigma_{\text{comp}} \left(1 - \frac{f_{\text{comp}}}{f_{CC}} \text{sgn}(v) \right) \quad (4)$$

where x is the displacement of the actuator, $v = \frac{dx}{dt}$ is the velocity of the actuator, f_{comp} is the compensation force, f_{CC} is the Coulomb force level, and σ_{comp} is the stiffness of the model.

The friction compensator prevents the friction in the tendon-drive system from being transmitted to the operator through the teleoperator. The effect of friction compensation on transparency of the teleoperator is evaluated by the friction force calculated in the output of the controller at two different phases:

- *Sliding mode:* During sliding mode, the compensator output reaches f_{CC} and the net friction force of the tendon system is $f_{C1} + f_{C2}$. If $f_{CC} = f_{C1} + f_{C2}$, then the friction forces are fully canceled.
- *Pre-sliding mode:* The compensator is in a transient state around zero velocity and does not provide an accurate compensation of the friction forces. However, the compensator preserves the stability of the teleoperator and does not cause friction-generated oscillations. This is discussed in Section VI.

VI. PASSIVITY OF THE COMPENSATION

Definition: Following [17], a system with flow V , effort F , and initial energy $e(0)$ ($V(t), F(t) \in \mathbb{R}^n$) is passive if

$$\int_0^t F(\tau)^T V(\tau) d\tau + e(0) \geq 0 \quad (5)$$

for all F , V , and $t \geq 0$.

We use passivity theory to explain the conditions under which the friction compensator described in the previous section preserves the stability of a teleoperator. The friction compensator and tendon-drive system for each joint are

grouped into one system with input v and output $f_{\text{total}} = f_{\text{friction}} - f_{\text{comp}}$ (Figure 4). The system is connected to the rest of teleoperator, which is assumed to be passive. The passivity of the system of Figure 4 then guarantees the stability of the teleoperator.

For the system of Figure 4, it is assumed

- 1) Friction forces of the tendon-drive system are modeled by (2).
- 2) The friction is compensated by the model of (4).

Then it is proved that the system of Figure 4 is passive if

$$\begin{aligned} f_{CC} &\leq f_{C1} + f_{C2}, \\ \sigma_{\text{comp}} &\leq \frac{2f_{C1}}{\Delta_{\text{max}}}, \end{aligned} \quad (6)$$

where Δ_{max} is the maximum displacement lag between the displacement of the actuator and the displacement of the tip joint.

The passivity of the system is investigated at two states:

- 1) $v = v_1 = v_2$, which corresponds to sliding motion in the actuator and tip joints.
- 2) $v = v_1$ and $v_2 = 0$, which corresponds to a sticking contact in the tip joint.

For the first case, the net friction force is calculated by:

$$\begin{aligned} f_{\text{friction}} &= f_{C1} \text{sgn}(v_1) + f_{C2} \text{sgn}(v_2) \\ &= (f_{C1} + f_{C2}) \text{sgn}(v), \end{aligned} \quad (7)$$

which represents a Coulomb model with Coulomb friction level $f_{C1} + f_{C2}$. It is shown in [13] that the compensator preserves the passivity of the system when

$$f_{CC} \leq f_{C1} + f_{C2}. \quad (8)$$

Since the force of the compensator is always less than the net friction force, the system is passive.

For the second state, the tip joint does not move and consequently the friction in that joint does not dissipate any energy. The tendon system remains in this state as long as the force transmitted through the tendon is less than the Coulomb friction level of the tip joint:

$$f_{\text{tendon}} \leq f_{C2}. \quad (9)$$

The above condition limits the maximum displacement of the actuator to:

$$\Delta_{\text{max}} = \frac{2f_{C2}}{k}, \quad (10)$$

where k is the stiffness of the tendon. We show that, when

$$\sigma_{\text{comp}} \leq \frac{2f_{C1}}{\Delta_{\text{max}}}, \quad (11)$$

the energy generated by the compensator is less than the energy dissipated by the friction in the actuator and the system is passive.

Figure 5 shows the force-displacement response of the actuator during a loop of the actuator displacement. The force response of the compensator is calculated by the following

Fig. 5. Generated energy and dissipated energy during one loop of friction movement.

implementable solution to the Dahl model (4) (see [13] for details):

$$\begin{aligned} f_{\text{comp}}^+ &= f_{CC} + (f_i - f_{CC}) \exp\left(\frac{-\sigma_{\text{comp}}}{f_{CC}}(x - x_i)\right) \\ f_{\text{comp}}^- &= -f_{CC} + (f_i + f_{CC}) \exp\left(\frac{\sigma_{\text{comp}}}{f_{CC}}(x - x_i)\right) \end{aligned} \quad (12)$$

where f_{comp}^+ is the compensation force for $v \geq 0$, f_{comp}^- is the compensation force for $v \leq 0$, f_i is the compensator force at the moment t_i when input velocity switches sign, and x_i is the displacement at that moment. x_i can be considered as an internal state of the friction compensator which is updated only at the moments that the input velocity switches sign. The energy generated by the compensator during the loop is calculated by:

$$E_{\text{comp}} = \int_{x_i - \Delta_{\text{max}}}^{x_i} (f_{\text{comp}}^+ - f_{\text{comp}}^-) dx. \quad (13)$$

This energy depends on f_i but it is maximized at $f_i = f_{CC}$. The maximum loop energy is calculated by substituting (12) into (13) where $f_i = f_{CC}$:

$$E_{\text{comp}} = \int_{x_i - \Delta_{\text{max}}}^{x_i} 2f_{CC} \left(1 - \exp\left(\frac{\sigma_{\text{comp}}}{f_{CC}}(x - x_i)\right)\right) dx. \quad (14)$$

It can be shown by using the Taylor series expansion, that for any x :

$$\exp(x) \geq (1 + x). \quad (15)$$

(14) and (15) conclude:

$$\begin{aligned} E_{\text{comp}} &\leq \int_{x_i - \Delta_{\text{max}}}^{x_i} 2f_{CC} \left(1 - \left(1 + \frac{\sigma_{\text{comp}}}{f_{CC}}(x - x_i)\right)\right) dx \\ E_{\text{comp}} &\leq \int_{x_i - \Delta_{\text{max}}}^{x_i} -2 \sigma_{\text{comp}}(x - x_i) dx \\ E_{\text{comp}} &\leq \sigma_{\text{comp}} \Delta_{\text{max}}^2. \end{aligned} \quad (16)$$

E_{friction} , the dissipated energy during the loop is calculated by:

$$E_{\text{friction}} = 2f_{C1} \Delta_{\text{max}}. \quad (17)$$

E_t , the total energy of the system shown in Figure 4, is calculated by:

$$E_t = E_{\text{friction}} - E_{\text{comp}} = 2f_{C1}\Delta_{\text{max}} - E_{\text{comp}}. \quad (18)$$

(16) and (18) conclude:

$$E_t \geq (2f_{C1} - \sigma_{\text{comp}}\Delta_{\text{max}})\Delta_{\text{max}}. \quad (19)$$

Finally, $E_t \geq 0$ if

$$\sigma_{\text{comp}} \leq \frac{2f_{C1}}{\Delta_{\text{max}}}. \quad (20)$$

The above proof can be extended to trajectories that consist of loops with a maximum displacement range Δ_{max} .

VII. EXPERIMENTAL RESULTS

We performed several experiments on the prismatic joint of a slave manipulator of a custom da Vinci telerobotic system [18], [19] (Figure 6) to demonstrate that the friction compensation techniques of this paper increase the transparency of the system and preserve the stability. The telerobotic system contains two master manipulators and two slave manipulators provided by Intuitive Surgical, Inc., and a custom control system developed at the Johns Hopkins University. The custom control system used position-tracking controllers to provide haptic feedback. Friction compensation was used for the prismatic joint of one of the slave manipulators.

A. Identification of Friction Parameters

In this section, we experimentally identify the parameters of the compensator model used for the prismatic joint including f_{CC} , the Coulomb friction level of the compensator model, and σ_{comp} , the stiffness coefficient of the compensator model.

The position-tracking teleoperator was used to identify the friction parameters. An operator moved the master manipulator to direct the prismatic joint of the slave manipulator to a desired trajectory. The desired trajectory was a back-and-forth displacement at low velocities and accelerations to ensure that Coulomb friction dominated over inertial forces and viscous friction.

Figure 7 shows the force-displacement response of the actuator during the back and forth displacement. The forces are obtained from the currents applied to the actuator. We subdivide the displacement range of the joint into three regions based on the slope of the force-displacement curve during positive velocity to study the motion of the joint:

- 1) *High-slope region*: the actuator and the tip joints are in pre-sliding motion.
- 2) *Low-slope region*: the actuator joint is in sliding motion and the tip joint is in pre-sliding motion.
- 3) *Zero-slope region*: the actuator and the tip joints are in sliding motion.

We fit the the force-displacement curve to friction model of (2). This way, one half of the size of the force change during high-slope region calculates $f_{C1} = 0.5/2$. The total

Fig. 6. The da Vinci surgical system components used in the experiments: (a) master telemanipulator (MTM) and (b) patient-side manipulator (PSM).

Fig. 7. Force-displacement response of a tendon-drive system. The force responses are subdivided into three regions to calculate the friction parameters: 1- high-slope region, 2- low-slope region, and 3- zero-slope region.

displacement change during high-slope and low-slope regions determine the maximum range of displacement during presliding $\Delta_{\text{max}} = 0.00012$ m. The amplitude of the force in zero-slope region calculates f_{CC} . Throughout this paper, all reported forces are normalized to the value of f_{CC} to respect proprietary data of Intuitive Surgical, Inc. The compensator stiffness is $\sigma_{\text{comp}} = \frac{0.5}{0.00012} = 4170$ using (11).

B. Transparency

We performed an experiment on the prismatic joint to show the effect of friction compensation on transparency. The prismatic joint was controlled by an operator through the position-tracking teleoperator to probe a piece of rubber. A Nano-17 ATI force sensor is attached to the tip of the slave manipulator to directly measure the force responses of the contact with the piece of rubber (Figure 8). The force from the sensor is only used to evaluate the friction compensation method, and is not used by the controller.

Fig. 8. Setup for measuring force responses of contact with a soft object.

Fig. 9. Force-displacement curves of a prismatic joint during probing of a soft object. The force curves shown are (1) the force response of the actuator of the joint, (2) the force response of the controller of the joint when Dahl-based friction compensation is applied, and (3) the force sensor output. Normalized forces are reported to protect proprietary data of Intuitive Surgical, Inc.

Figure 9 shows force-displacement responses of the prismatic joint during probing of the piece of rubber. The friction compensation was applied during the whole test, however, the force response of the position-tracking controller before being added to the compensator force is considered as the force response of the controller without friction compensation. Friction compensation increases the match between force curves of the user and the soft object when friction is compensated. Thus, transparency improves when friction compensation is used.

C. Stability

Several experiments were performed on the prismatic joint to verify the effects of the parameters of the compensators on the stability of the prismatic joint. Experimental results showed that the joint motion was stable as long as the stiffness and the Coulomb friction level of the compensator were within the passivity margin of (6).

VIII. CONCLUSION

This paper introduced a friction compensation model to cancel friction in a tendon-drive mechanism of a manipulator of a teleoperator. It was shown that a low-stiffness Dahl model whose stiffness is less than the tendon, provided passive friction compensation and improved the transparency of the teleoperator during a sliding mode.

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