Friction Compensation for a Force-Feedback Telerobotic System

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***Abstract*— This paper presents a model-based approach to cancel friction in the joints of the manipulators of a force-feedback telerobotic system. Friction compensation can improve the transparency of telerobotic systems, where transparency is quantified in terms of a match between the impedance of the environment and the impedance transmitted to the user. We used Dahl friction models to compensate for physical friction in the device. Experiments performed on a telerobotic system demonstrated that teleoperation transparency is improved by using these models. Further, the stability of the teleoperation is analyzed using passivity theory, and it is shown that the master-slave system remains stable up to a certain level of friction compensation.**

I. Introduction

Force feedback improves the performance of telerobotic systems by providing a feeling of telepresence. In a system with perfect transparency, the force that the user feels when he moves the master manipulator is equal to the force he would feel if he were directly manipulating the environment. The main factors preventing perfect transparency in teleoperation include transmission delay, device friction, and device mass.

Force feedback may enhance the performance of robot-assisted surgical systems [1]. A teleoperated surgical-assistant system consists of master manipulators and slave manipulators, where the master manipulators provide position commands that are followed by the slave manipulators. A surgeon uses the master manipulators (typically one for each hand) to direct the slave manipulators to move surgical instruments to desired locations in the patient's body. Force-feedback is critical in certain surgical tasks, such as suturing. In cardiac surgery, haptic feedback of the forces applied during suturing helps the operator to create knots that are firm enough to hold, but do not damage tissue [2].

Because of the significant practical limitations of applying force sensors in robot-assisted surgery (due to geometry, size, biocompatibility, and sterilization), we seek to develop force feedback methods that do not require force sensors. Thus, the underlying method of providing force feedback to the operator is a position-position control law [3]. In robot-assisted surgery systems where transmission delays are negligible and a position-position control law is used, we hypothesize that the friction in the manipulators has the greatest affect on transparency, especially for low bandwidth motion. It is difficult to have transparent force feedback in surgical-assistant systems because the interaction forces between the slave robot and the tissue are often on the same scale as the friction forces in the joints. Thus, in many tasks, such as suturing, cutting, and retraction, the friction forces mask the applied forces and the surgeon will not receive useful haptic feedback. If the force feedback gain is increased in an effort to display instrument-tissue interaction forces, the corresponding increase in friction force feedback will also contribute to user fatigue.

In this paper, we used a model-based approach to reduce friction in the joints of a telerobotic system. The friction in each joint was compensated by a Dahl friction model. The Dahl model was originally introduced to estimate friction forces between two hard objects during pre-sliding contact [4]. However, in this paper, we used the advantageous mathematical properties of the Dahl model to develop a friction-compensated, stable telerobotic system. Several experiments were performed on a telerobotic system to demonstrate that our model-based scheme improved the transparency of the telerobotic system, and the system remained stable up to a certain level of friction compensation. The stability of the compensated telerobotic system was also investigated analytically using passivity theory.

The rest of this paper is organized as follows: Section II reviews related work. Section III explains the Dahl model and the friction compensation method. Section IV analyzes the transparency and stability of a telerobotic system with friction compensation. Section V concludes the paper and provides areas for future work.

II. Related Work

Armstrong et al. [5] and Olsson et al. [6] surveyed various friction compensation techniques and friction models used for minimizing tracking errors of control systems. Dahl introduced a dynamic model to estimate the friction between two plates separated by ball bearings [4]. We use the Dahl model to compensate friction in the joints of the manipulators of a telerobotic system. The LuGre (Lund Grenoble) model is an extension of the Dahl model that captures more static and dynamic properties of friction [7].

Various control techniques have been introduced in the last two decades to provide stable teleoperation with a high degree of transparency; see [8] for a survey. Stability and transparency are conflicting design goals for a telerobotic system [3]. The network representation of a teleoperation system is commonly used to analyze transparency and stability. Passivity theory is generally used as a tool for ensuring the stability of teleoperation [8].

Passivity theory has also been used to prove the stability of tracking control systems with observer-based friction compensators that applied LuGre models [6], [9]. The overall tracking control system consists of the connection of two passive subsystems. One subsystem described the tracking controller and the other the friction compensator. The passivity of both subsystems together guarantees global asymptotic position tracking. In this paper, we use passivity theory to confirm the stability of force-feedback telerobotic systems using Dahl model-based friction compensators. Here, no observation of internal states is required.

Friction modeling has been studied for haptic rendering and compensation of friction in haptic displays. Hayward and Armstrong [10] described a dynamic friction model that does not drift. They used that model for haptic rendering of friction. Richard and Cutkosky [11] presented a modified Karnopp friction model for haptic rendering of friction. They reported that user performance of a targeting task was nearly identical for real and simulated friction. In [12], 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 [13], 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 telerobotic systems.

III. Model-Based Friction Compensation

In model-based compensation, a model is first established to estimate friction. Then the output of the model is added to the control command of the system to compensate friction. In this section, we describe the Dahl model and its properties, and use the model to compensate friction in a slave joint of a telerobotic system designed for robot-assisted surgery.

A. Dahl model

The general model proposed by Dahl has the form:

$$\frac{df}{dx} = \sigma \left(1 - \frac{f}{f_c}\,\mathrm{sgn}(v)\right)^{\alpha}, \qquad (1)$$

where x is the displacement, $v = \dot{x}$ is the velocity, f is the friction force, f_c is the Coulomb force level, σ is the stiffness coefficient, and α defines the shape of the strain-stress curve. We take $\alpha = 1$ in this paper. The friction force f is bounded: $-f_c \leq f \leq f_c$.

The Dahl model has useful mathematical properties. It is rate independent. Around zero velocity, it generates smooth force and creates a hysteresis loop whose size can be adjusted by the stiffness coefficient. These properties allow us to compensate friction when there is a small lag between the displacement input to the friction compensator and the displacements of some of contact surfaces. For example, in manipulators with tendon transmission, the displacements measured by the encoders are slightly different from the displacements of the frictional surfaces at the joints of the manipulator.

A time-domain representation of the Dahl model can be obtained from (1) for $\alpha = 1$:

$$\frac{df}{dt} = \frac{df}{dx}\frac{dx}{dt} = \frac{df}{dx}v = \sigma\ v\ \left(1 - \frac{f}{f_c}\,\mathrm{sgn}(v)\right). \qquad (2)$$

By using Euler's backward difference, a discrete-time implementation of (2) is obtained by:

$$f_{i+1} = f_i + T\ \sigma\ v_i\ \left(1 - \frac{f_i}{f_c}\,\mathrm{sgn}(v_i)\right), \qquad (3)$$

where f_i and f_{i+1} represent forces at time t_i and t_{i+1} respectively, v_i is the velocity at t_i, and $T = t_{i+1} - t_i$. This model can be viewed as a discrete-time linear filter:

$$f_{i+1} = \left(1 - \frac{\sigma\ |v_i|}{f_c}\right) f_i + T\ \sigma\ v_i, \qquad (4)$$

where v_i is the input. The filter has a velocity variable pole at $z = 1 - \frac{\sigma\ |v_i|}{f_c}$. Therefore, the filter becomes unstable at high velocities, when the pole is outside the unit circle $z = 1$. Experiments also reveal that (4) exhibits instability at high velocities.

Thus, we use an alternative approach to derive a discrete-time representation of the Dahl model that never becomes unstable. For, $v \geq 0$, the Dahl model becomes:

$$\frac{df}{dx} = \sigma \left(1 - \frac{f}{f_c}\right). \qquad (5)$$

The above equation is a first order linear differential equation and its general solution is:

$$f = f_c + a\ e^{-\frac{\sigma}{f_c}x}. \qquad (6)$$

where a is a constant that depends on the initial value of the force at the moment that the motion reverses. A recursive relationship between f_{i+1} and f_i is obtained by calculating (6) at times t_{i+1} and t_i:

$$f_{i+1} = f_c + (f_i - f_c)\ e^{-\frac{\sigma}{f_c}(x - x_i)}. \qquad (7)$$

For $v \leq 0$, our approach concludes:

$$f_{i+1} = -f_c + (f_i + f_c)\ e^{\frac{\sigma}{f_c}(x - x_i)}. \qquad (8)$$

(7) and (8) can be combined to give:

$$f_{i+1} = f_c\ \mathrm{sgn}(v_i) + (f_i - f_c\ \mathrm{sgn}(v_i))\ e^{-\frac{\sigma}{f_c}\ |x - x_i|}. \qquad (9)$$

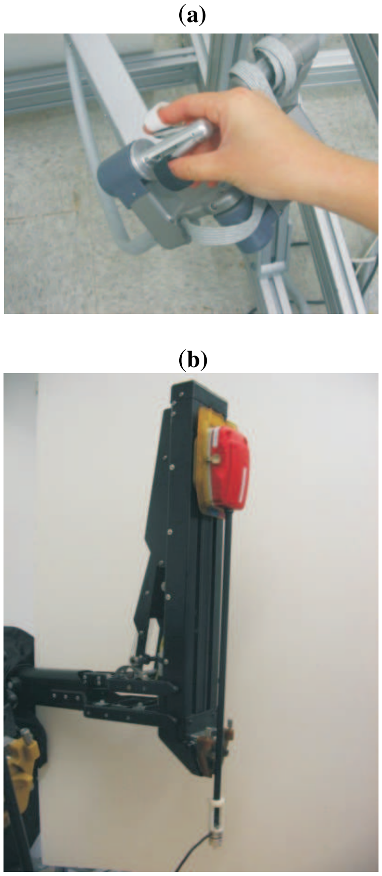

Fig. 1. Da Vinci master telemanipulator (MTM) and patient-side manipulator (PSM) used in experiments. **(a)** MTM. **(b)** PSM.

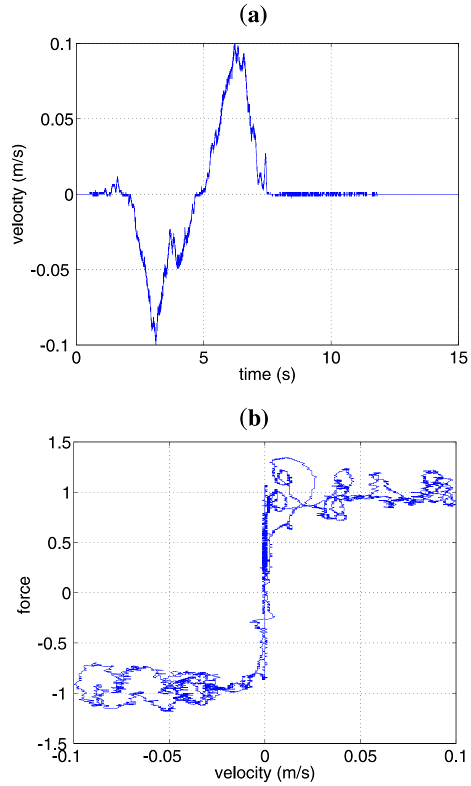

Fig. 2. Estimating friction in the prismatic joint of the patient-side manipulator of a da Vinci telerobotic system. **a)** The velocity response. **b)** The normalized force-velocity response.

B. Model Identification

In this section, we identify f_c, the Coulomb friction level, and σ, the stiffness coefficient of the Dahl model. f_c is determined from the force-velocity curve of the joint obtained for a smooth motion. We performed several experiments on a telerobotic system to estimate friction in its joints. The telerobotic system consists of a da Vinci master telemanipulator (MTM) and patient-side manipulator (PSM) [14], [15] with customized hardware and software (Figure 1). Figure 2 shows the force-velocity curve obtained for the prismatic joint of the patient-side manipulator. Based on the force-velocity curve, f_c is estimated. Throughout this paper, all reported forces are normalized to the value of f_c to respect proprietary data.

The parameter σ is calculated during friction compensation. It is obtained by the maximum σ of a compensator that does not cause oscillation in the system. This σ will be much less that the friction stiffness between two hard objects and it depends on the non-idealities of the telerobotic systems such as the compliance of transmission tendons.

C. Friction Compensation for a Telerobotic System

Figure 3 shows a network model of a teleoperation system consisting of five subsystems: the human operator (user), the master manipulator, the slave manipulator, the controller, and the environment. The master, slave, and controller are grouped together as a teleoperator system. The goal is to design a controller that creates a passive and transparent teleoperator. We assume there is no transmission delay.

A position-position control architecture is used to design the controller [3]. This architecture does not require any force measurement, making it especially practical for medical application. The controller calculates the errors between the position and the orientation of corresponding points on the master and slave manipulators in a Cartesian frame and applies forces and torques proportional to those errors. Let X_m and X_s be 6-element vectors of position and the orientation of the specified points in Cartesian space. F_m and F_s, the forces and torques applied to the specified points, are calculated by:

$$F_m = -F_s = P(X_m - X_s) \tag{10}$$

where P is a 6×6 gain matrix. The position-position controller can be imagined as a network of six springs that connects the specified points of the master and slave manipulators. Friction compensation is performed in joint space. Consider the joint j of the slave manipulator and assume that x and v are the displacement and velocity or, in the case of a revolute joint, angular displacement and angular velocity of the joint. (To simplify the mathematical representation, the index j is not shown.) $f_{_{dahl}}$, the friction compensation force in joint j, is calculated by a Dahl model, whose parameters $\sigma_{_D}$ and $f_{_D}$ are identified by using the approach of Section III-B. $f_{_{total}}$,

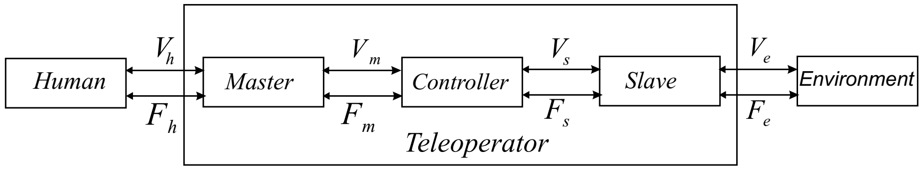

Fig. 3. The network representation of a telerobotic system.

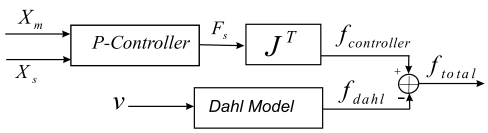

Fig. 4. Friction compensation for a telerobotic system.

the total force (or torque) applied to the joint is obtained by subtracting $f_{controller}$, the force calculated by the controller, from f_{dahl} (Figure 4):

$$f_{total} = f_{controller} - f_{dahl} \tag{11}$$

IV. Performance of a Telerobotic System with Friction Compensation

The performance of a telerobotic system with friction compensation is evaluated in terms of its transparency and stability.

A. Transparency

Transparency of a telerobotic system is generally quantified in terms of a match between the impendence of the environment and the impedance transmitted to the user. Here, we study the transparency of a position-position telerobotic system at low frequencies by comparing the force-displacement curve of the environment with the force-displacement curve at the user's hand. Impedance match at low frequencies is essential for telemanipulation in soft environments. The elastic properties of the objects will be correctly reflected to the user if the telerobotic system is transparent at low frequencies.

We performed several experimental tests on a da Vinci MTM and PSM system to (Figure 1) to demonstrate that the friction compensation techniques of this paper increase the transparency of the system. During these tests, the friction compensation was only applied to the slave manipulator whose friction forces are much greater than the master one. The interaction forces between the master manipulator and the user are estimated by the electrical currents applied to the actuators of the Master. Two sets of tests were performed as follows.

1) Free Space Movement: When the slave manipulator does not contact any object in the environment, the user should feel no resistance. Here, we compare the force responses of the da Vinci system with and without friction compensation when the slave manipulator moves in free space (Figure 6). Friction compensation reduces the force applied to the user.

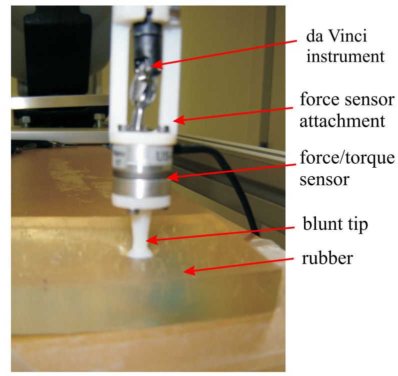

Fig. 5. Setup for measuring force responses of contact with a soft object.

2) Contact with a Soft Object: Here, we compare the force response of the da Vinci system when the slave manipulator contacts a piece of soft rubber. A 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 5). The force from the sensor is only used to evaluate the friction compensation method, and is not used by the controller.

As the force-displacement curves in Figure 7 show, 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.

B. Stability

Passivity of a teleoperator guarantees stability of teleoperation when both the user and environment are passive. Here, we prove that a passive teleoperator with Coulomb friction remains passive when the friction in the system is compensated up to a certain level using a Dahl model.

Definition: Following [16], a system with flow V, effort F, and initial energy $e(0)$; $V(t), F(t) \in \mathbb{R}^n$ is passive, if

$$\int_0^t F(\tau)^T V(\tau) d\tau + e(0) \geq 0 \tag{12}$$

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

Suppose $f_{coulomb}$ expresses Coulomb friction in joint j of a passive teleoperator:

$$f_{coulomb} = f_C \ \operatorname{sgn}(v) \tag{13}$$

where v is the velocity of joint j and f_C the Coulomb force level. Assume the friction in joint j is compensated by a Dahl

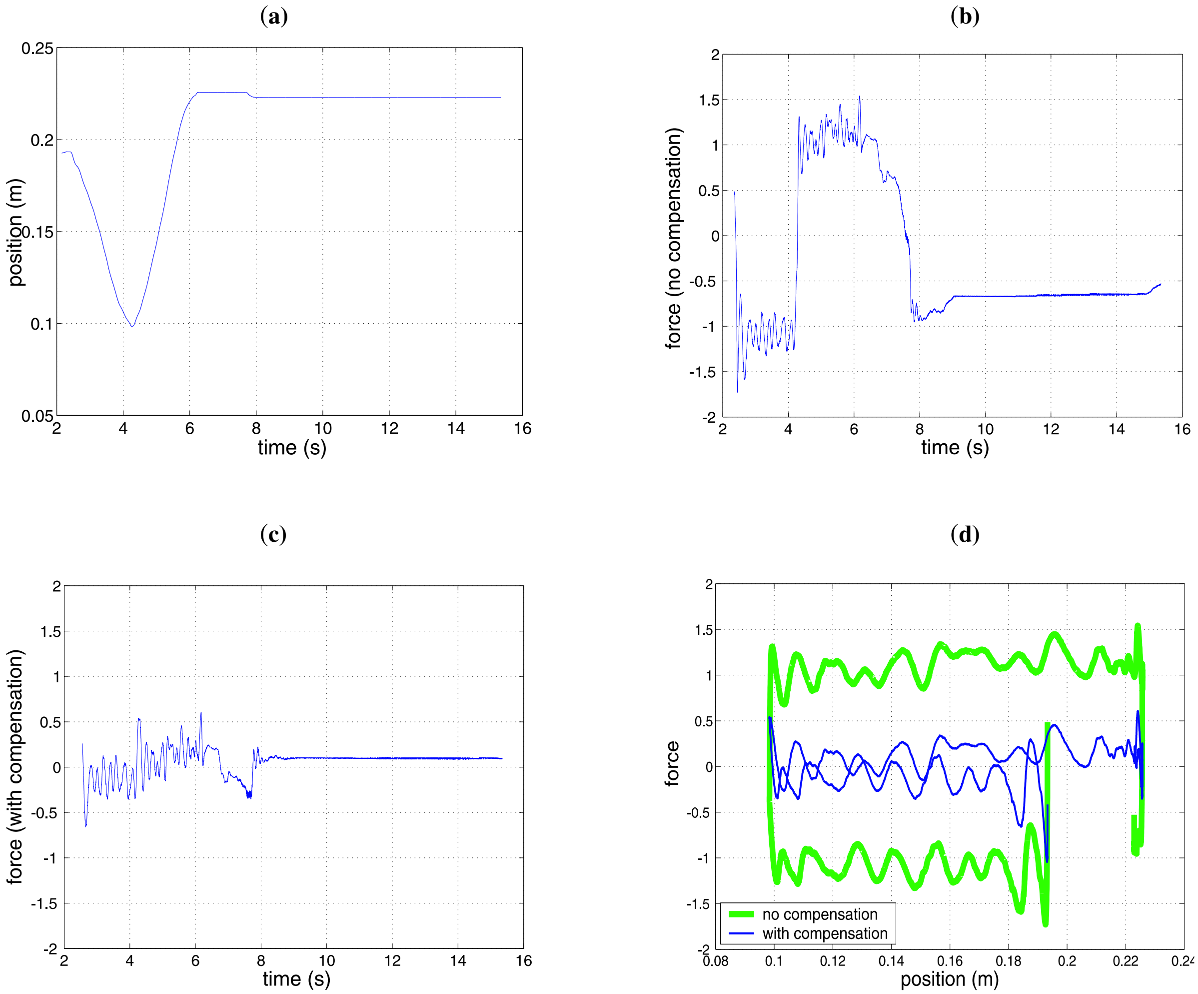

Fig. 6. Forces applied to the user when the slave manipulator moves in free space. **(a)** Displacement response. **(b)** The force applied to the user when there is no friction compensation. **(c)** The force applied to the user when there is a friction compensation. **(d)** Force-displacement responses (force with no friction compensation is shown by a thick line and the force with friction compensation is shown by a thin line).

model with σ_D and f_D:

$$\frac{df_{dahl}}{dt} = \sigma_D v \left(1 - \frac{f_{dahl}}{f_D}\,\mathrm{sgn}(v)\right). \tag{14}$$

We show that for

$$f_C \geq f_D, \tag{15}$$

the teleoperator remains passive when friction is compensated.

We group the Dahl friction compensator and the model for Coulomb friction into one system with input v and output $f_{coulomb} - f_{dahl}$ (Figure 8). This system is connected to the rest of teloperator. For the Dahl model, we always have

$$|f_{dahl}| \leq f_D. \tag{16}$$

Multiplying by $|v|$, we get

$$f_{dahl}\ v \leq |f_{dahl}|\ |v| \leq f_D\ |v|. \tag{17}$$

By combining (15) and (17), we conclude

$$f_{dahl}\ v \ \leq\ f_C\ |v|, \tag{18}$$

$$f_{dahl}\ v \ \leq\ f_{coulomb}\ v, \tag{19}$$

$$(f_{coulomb} - f_{dahl})\ v \ \geq\ 0. \tag{20}$$

Integrating the above equation concludes

$$\int_0^t (f_{coulomb} - f_{dahl})\ v\ d\tau \geq 0, \tag{21}$$

which proves the passivity of the system.

We performed several experiments with the prismatic joint of the da Vinci system. The system starts going unstable when the level of Coulomb friction of the compensator becomes greater than the Coulomb force level identified for the joint.

V. Conclusion

The Dahl model is used to compensate friction in the joints of a telerobotic system. Friction compensation improves the transparency of the teleoperation system, where the transparency is expressed in terms of a match between

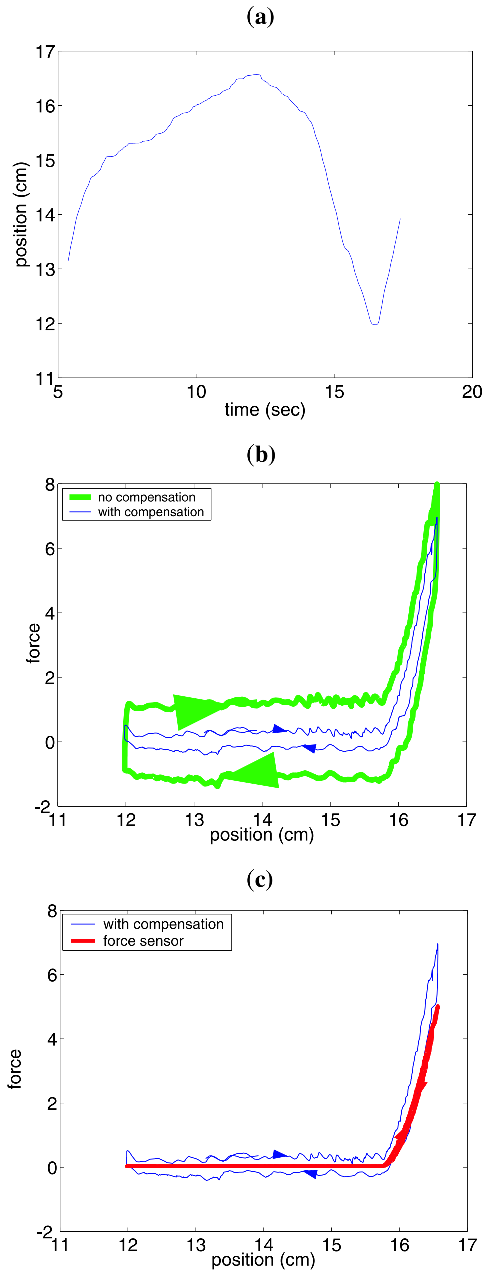

Fig. 7. Forces applied to the user and slave manipulator during contact with a soft object. **a)** Displacement response. **b)** User force-displacement curve when friction is compensated (thin line) is compared with user force-displacement curve without friction compensation (thick line). **c)** User force-displacement curve when friction is compensated (thin line) is compared with force-displacement curve of the soft object measured by a force sensor attached to the slave manipulator (thick line).

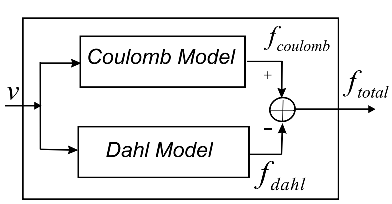

Fig. 8. Passive friction compensation.

the force-displacement curve of the environment and the force-displacement curve at the user. The passivity of the teleoperator can be lost due to friction compensation. However, we showed that if the level of the friction compensation of the Dahl model was less than the level of Coulomb friction of the joint, the teleoperator remains stable. Future work will consider the passivity of a teleoperator considering a more complex model that can handle drive cable dynamics. In this case, the friction in each joint is modeled by two Coulomb friction models, which simulate frictional contacts at both ends of the drive cable.

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