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DISTURBANCE OBSERVER BASED CLOSED LOOP FORCE CONTROL FOR HAPTIC FEEDBACK

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ABSTRACT

Most commonly used impedance-type haptic interfaces employ open-loop force control under the assumption of pseudo-static interactions. Advanced force control in such interfaces can increase simulation fidelity through improvement of the transparency of the device, and can further improve robustness. However, closed loop force-feedback is limited both due to the bandwidth limitations of force sensing and the associated cost of force sensors required for its implementation. In this paper, we propose the use of a nonlinear disturbance observer for estimation of contact forces during haptic interactions. This approach circumvents the traditional drawbacks of force sensing while exhibiting the advantages of closed-loop force control in haptic devices. The feedback of contact force information further enables implementation of advanced robot force control techniques such as robust hybrid impedance and admittance control. Simulation and experimental results, utilizing a PHANToM Premium 1.0A haptic interface, are presented to demonstrate the efficacy of the proposed approach.

INTRODUCTION

Force or haptic feedback can enhance a user's feel of realism in a virtual environment simulation by conveying touch-related sensory information to the user. The user can be conveyed information about physical attributes of the simulated objects, like hardness, texture or inertia through haptic feedback. It is also possible to simulate additional physical forces and fields, which may or may not be part of a natural environment, in order to convey information to the user. This makes a haptic display suitable for a variety of applications like remote operation in hazardous environments and simulators for surgical training [1–3].

According to Massie and Salisbury [4] the following three criteria are employed in the design of haptic mechanisms:

- Free space must feel free;
- Solid virtual objects must feel stiff; and
- Virtual constraints must not be easily saturated.

The first criterion implies that apparent inertia and viscosity of the device should be as low as possible. The second criterion implies that the haptic interface should be able to generate sufficiently high stiffness to emulate contact with a rigid object. A stiff mechanism and high bandwidth controller are required to simulate high stiffnesses. The last criterion implies that the force output of the device should be high enough to simulate solid objects.

Fidelity of a haptic interface is characterized by the level of impedance discrimination that can be detected at the interface [5]. The primary hindrance to achieving high fidelity are the dynamics of the haptic device, as they appear to the user as a part of the simulated environment. Low force output devices can be designed to have low dynamic properties with use of efficient drive trains (cable, harmonic drives) and high strength-to-weight materials. Counterbalancing can also be used to to remove gravitational effects, although at the cost of increased inertia.

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However, when larger force output is desired, it becomes increasingly difficult to passively reduce dynamic effects of manipulator dynamics. High force output devices require use of larger actuators, drive mechanisms, and linkages leading to increased inertia and friction in the device. Even if the force output is adequate, the dynamics of the device can hinder high fidelity required for display of some details in the environment, which can degrade performance in dexterous tasks.

Active control is needed for further reductions in haptic device dynamics. This can be achieved either through model feedforward or force feedback from a sensor mounted at the human-device interface. While model feedforward can improve performance, it is very susceptible to modeling errors as the impedance displayed by the device will be incorrect in presence of such errors. Carignan and Cleary [5] note that while closed loop force feedback controllers offer a possible solution for reducing device dynamics, the use of force/torque sensors in haptics is limited due to added mass and cost considerations. In this paper the authors present a nonlinear disturbance observer for sensorless closed loop control of haptic interfaces.

Katsura et. al note that use of force sensors for closed loop force control is limited due to their limited bandwidth and high cost [6]. As a force sensor employs a strain gauge, it introduces some compliance into the structure of the robot. In order to alleviate the instability associated with force control, large viscous gains are required that slow the robot response. Instead they propose the use of a disturbance observer as a force sensor for contact force control, and demonstrate the efficacy of the same in improving force control performance. Their proposed approach employs a linear plant model for the observer design, thereby requiring the nonlinear components to be canceled separately. In comparison, the method presented in this paper employs a nonlinear disturbance observer and requires no additional modeling or computation. Exponential convergence of the nonlinear disturbance observer for constant disturbances is also shown.

The rest of the paper is organized as follows. The next section presents an overview of the haptic controller architectures. Subsequently, the nonlinear disturbance observer design is presented. To conclude, simulation and experimental results, demonstrating the applicability of disturbance observer base force estimation to closed loop haptic control, are presented.

HAPTIC CONTROL DESIGN

Figure 1 shows a typical haptic system setup in the impedance mode architecture. The interface comprises of the human operator, the haptic device and the virtual environment simulation. Visual interface to the environment may also be present. The human operator imposes motion on the haptic device, which exerts forces back to the operator. Sensors on the device measure position and these position signals are then used to compute changes in the virtual environments. The model of the virtual environment computes desired forces at the human-robot interface based upon the position of the robot and environmental properties. The haptic controller determines motor torque based upon sensed position and/or force and the desired interaction forces as computed by the virtual environment model.

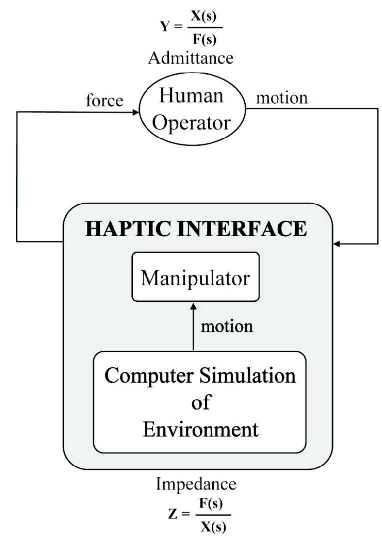

Figure 1. Haptic Operator-Interface Loop

Control architectures for haptic interfaces can be broadly classified into two classes: impedance control and admittance control. Impedance controlled systems measure the motion commanded by the user and control the force reflected back by the device. Conversely, admittance controlled interfaces measure the force applied by the user and control the velocity or position of the device. In some cases, force or displacements can be used as additional inputs to the impedance or admittance controllers respectively.

Open Loop Impedance Control

Conventionally, control of most haptic interfaces is achieved through an open loop impedance controller. Figure 2 depicts the block diagram for an open loop impedance controller, where the linearized device dynamics are represented by $\mathbf{Z}_m$. Sensors mounted on the haptic device measure the position of the tool tip, $\mathbf{x}$. The controller takes this position of the device, and multiplies it with the environment impedance, $\mathbf{Z}_e$, to obtain the desired force output $\mathbf{F}_d$. The desired end-effector force, $\mathbf{F}_d$ is mapped to corresponding motor torques through the Jacobian, $\mathbf{J}$. Note that $\mathbf{F}$ is an external force applied by the human operator to move the device and $\mathbf{Z}_h$ is the human impedance.
The following relationships describe an open loop haptic interaction

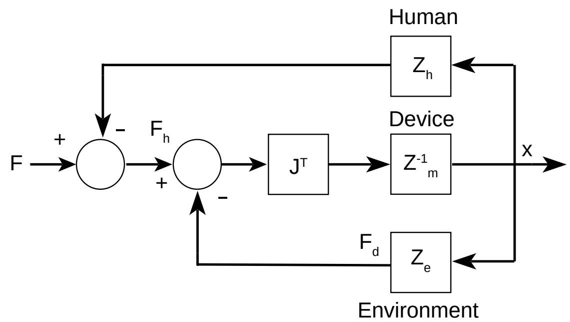

Figure 2. Open loop impedance control of a haptic interface

$$\tau = \mathbf{J}^{\mathrm{T}}\mathbf{F}_d \tag{1}$$
$$\mathbf{F}_d = \mathbf{Z}_e\mathbf{x} \tag{2}$$

where, τ is the motor torque. The closed loop impedance, $\mathbf{Z}_{cl}$, which is the relationship between force applied by the operator, $\mathbf{F}$ and device displacement, $\mathbf{x}$ is the sum of the desired impedance, $\mathbf{Z}_e$, human impedance, $\mathbf{Z}_h$, and the device impedance, $\mathbf{Z}_m$ [5]. Thus, the operator feels the haptic device impedance in addition to the desired environment impedance.

$$\mathbf{Z}_{cl} = \mathbf{Z}_e + \mathbf{Z}_m + \mathbf{Z}_h \tag{3}$$

Impedance Control with Force Feedback

Figure 3 depicts an impedance controller with force feedback. As compared to the standard impedance controller, shown in Figure 2, sensed forces are now fed back to the haptic controller to close the force control loop.

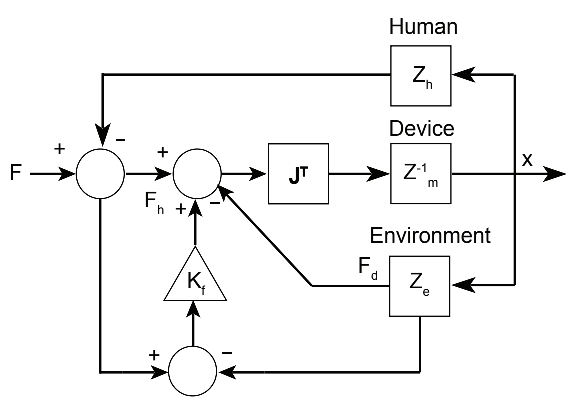

Figure 3. Impedance control with force feedback

$$\tau = \mathbf{J}^{\mathrm{T}}(\mathbf{F}_d + K_f(\mathbf{F}_d - \mathbf{F}_h)) \tag{4}$$

where $\mathbf{F}_d$ is given by Equation (2); K_f is the force gain; and $\mathbf{F}_u$ is the external force acting on the robot end-effector. Note that during impedance display with force-feedback, errors due to dynamic of the haptic device are inversely proportional to $1 + K_f$ [5]. The closed loop impedance is given by

$$\mathbf{Z}_{cl} = \mathbf{Z}_e + (I + K_f)^{-1}\mathbf{Z}_m + \mathbf{Z}_h \tag{5}$$

The force gain is typically set as high as determined by the stability of the interface.

NONLINEAR DISTURBANCE OBSERVER DESIGN

The model of a n-link robot manipulator can be written as:

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \mathbf{T} + \mathbf{d} \tag{6}$$

where $\mathbf{q} \in \mathbb{R}^n$ is the vector of joint positions; $\dot{\mathbf{q}} \in \mathbb{R}^n$ is the vector of joint velocities; $\ddot{\mathbf{q}} \in \mathbb{R}^n$ is the vector of joint accelerations; $\mathbf{D}(\mathbf{q}) \in \mathbb{R}^{n\times n}$ is the inertia matrix; $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} \in \mathbb{R}^n$ is the vector of Coriolis and centrifugal forces; $\mathbf{G}(\mathbf{q}) \in \mathbb{R}^n$ is the vector of gravitational forces; $\mathbf{T} \in \mathbb{R}^n$ is the vector of applied torques; and $\mathbf{d}$ is the vector of external disturbances.

Similar to the approach presented in [7], we define an auxiliary variable vector

$$\mathbf{z} = \hat{\mathbf{d}} - \mathbf{p}(\mathbf{q},\dot{\mathbf{q}}) \tag{7}$$

where $\mathbf{z} \in \mathbb{R}^n$; $\hat{\mathbf{d}} \in \mathbb{R}^n$ is the vector of disturbance estimates; and $\mathbf{p}(\mathbf{q},\dot{\mathbf{q}})$ is to be determined.
Then, define a nonlinear function $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})$ such that,

$$\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} = \frac{\mathrm{d}\mathbf{p}(\mathbf{q},\dot{\mathbf{q}})}{\mathrm{d}t} \tag{8}$$

Let $\dot{\hat{\mathbf{d}}}$ be defined by the following equation

$$\dot{\hat{\mathbf{d}}} = -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\hat{\mathbf{d}} + \mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(q) - \mathbf{T}) \tag{9}$$

Differentiating (7)

$$\dot{\mathbf{z}} = -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{z}+\mathbf{p}(\mathbf{q},\dot{\mathbf{q}}))+\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q})-\mathbf{T})-\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{D}(q)\ddot{\mathbf{q}} \tag{10}$$
$$= -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{z}+\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})-\mathbf{T}-\mathbf{p}(\mathbf{q},\dot{\mathbf{q}})) \tag{11}$$

The error in force estimation is then given by,

$$\mathbf{e} = \mathbf{d} - \hat{\mathbf{d}} \tag{12}$$

Since no prior information about the disturbance is available, we assume that $\dot{\mathbf{d}} = 0$. Then differentiating (12), we have

$$\dot{\mathbf{e}} = \dot{\mathbf{d}} - \dot{\hat{\mathbf{d}}} \tag{13}$$
$$= -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{e} \tag{14}$$

Hence, the estimation $\hat{\mathbf{d}}$ converges to $\mathbf{d}$ if the function $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})$ is such that (14) is asymptotically stable. Therefore, $\mathbf{p}(\mathbf{q},\dot{\mathbf{q}})$ should be selected such that the function $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})$ defined by (8) satisfies the stability condition for (14). Although, in general it is not easy to select such a function, in the case of robotic manipulators the choice of $\mathbf{p}(\mathbf{q},\dot{\mathbf{q}}) = c\dot{\mathbf{q}}$, where c is a positive scalar, is sufficient to guarantee convergence.

$$\mathbf{p}(\mathbf{q},\dot{\mathbf{q}}) = c\dot{\mathbf{q}} \tag{15}$$

Using (8),

$$L(\mathbf{q},\dot{\mathbf{q}}) = c\mathbf{D}^{-1}(\mathbf{q}) \tag{16}$$

For robotic manipulators the inertia matrix $\mathbf{D}(\mathbf{q})$ is symmetric and positive-definite, hence $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}}) = c\mathbf{D}^{-1}(\mathbf{q})$ is also a symmetric, positive-definite matrix. Thereby , (14) is exponentially stable.

Next, define a Lyapunov function candidate

$$V(\mathbf{e}) = \frac{1}{2}\mathbf{e}^{\mathrm{T}}\mathbf{e} \tag{17}$$

Differentiating (17) along the observer trajectory gives

$$\dot{V}(\mathbf{e}) = -c\mathbf{e}^{\mathrm{T}}\mathbf{D}^{-1}(\mathbf{q})\mathbf{e} \tag{18}$$
$$< 0 \tag{19}$$

As $\frac{\mathrm{d}V(\mathbf{e})}{\mathrm{d}t} < 0, \forall \mathbf{e}, t$, (14) is exponentially stable and the rate of convergence is proportional to c.

RESULTS AND DISCUSSION

The proposed disturbance observer is employed as a force sensor for closed loop control of haptic interfaces. It is assumed that the forces exerted by the human operator are the only external forces acting on the device. Simulations were performed for display of virtual walls using the commercially available PHANToM 1.5 haptic interface. The dynamic model presented by Cavusoglu and Feygin [8] has been employed for this purpose.

Free Movement Simulation

The disturbance observer has been designed under the assumption of constant external forces. In order to test the performance of the observer in estimating continuously changing forces, simulations were performed with the robot moving freely under the action of gravity. A disturbance observer was implemented using a model of the robot that did not include the gravity terms. The value for the observer gain, c, was chosen as 2. Figure 4 shows the results for second and third joints of the robot. Note that the base joint of the robot is not affected by gravity and hence, not shown. The observer shows excellent tracking performance and successfully estimates gravitational torques on the robot.

Impedance Control with Force-feedback

Figures 5 and 6 show simulation results of the interaction of the robot with a virtual wall, of stiffness $1000N/m$ located at $y = -0.01m$, under impedance control with force-feedback for $K_f = 1$ and $K_f = 50$ respectively. Solid lines show the displacement of the end-effector when the disturbance observer was employed as the force sensor, whereas dashed lines represent performance when exact external forces were provided to the controller. For the purpose of this simulation, no human model was incorporated and the device was allowed to move under gravity. Note that this is the worst case scenario for impedance displays, as the operator can stabilize the system by providing damping. Also, notice that increasing the gain tends to destabilize the system, as evident from increased oscillations when force gain is set to 50. For both control gains, the performance of the disturbance observer based controller is almost indistinguishable from the case when exact forces were provided to the controller.

Experimental Results Experiments were conducted using a PHANToM 1.0 haptic interface, running on a Labview FPGA platform. Dynamic parameters presented in [9] were employed for observer design. Figure 7 shows the interaction of the user with a virtual wall of stiffness $1000\ N/m$ located at $y = 0.01\ m$. A closed loop force control gain, K_f, of 0.1 was found to give

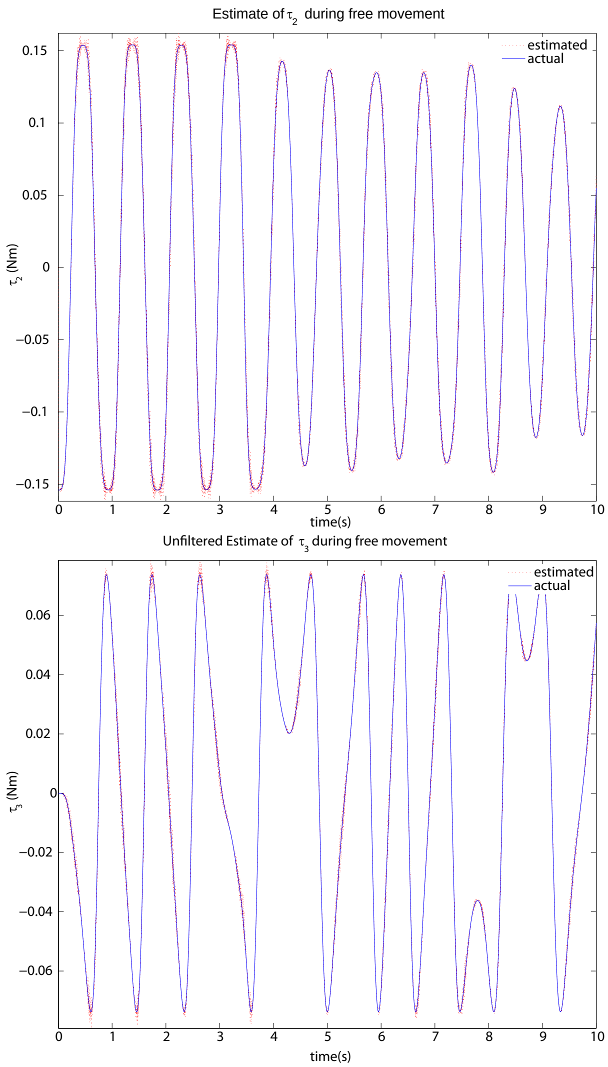

Figure 4. Estimation of gravity terms using the disturbance observer

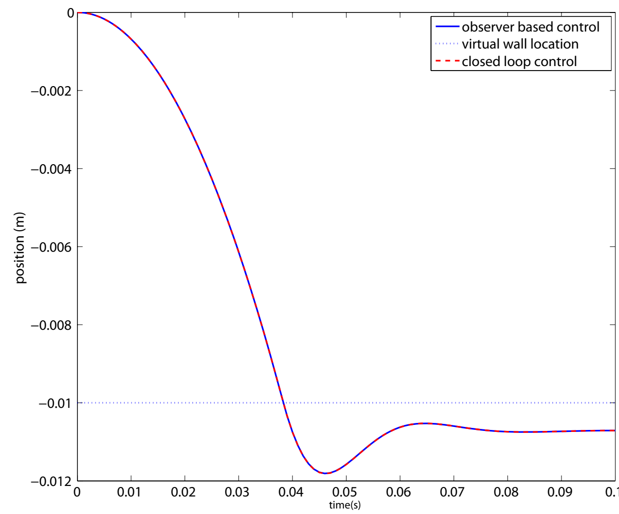

Figure 5. Virtual wall interaction under impedance control with force feedback, Kf = 1 (simulation)

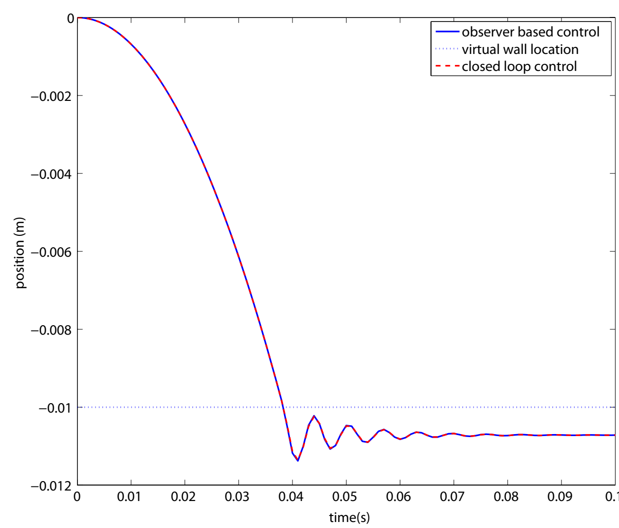

Figure 6. Virtual wall interaction under impedance control with force feedback, Kf = 50 (simulation)

best performance, with higher gains resulting in vibrations on contact. This can be expected as the PHANToM is designed to have inherently small natural dynamics and improvements that can be achieved over open loop impedance control are small. Figure 8 shows the corresponding contact force at the endpoint as estimated by the disturbance observer. It should be noted that the command torque values available to the the disturbance observer were not saturated at the maximum output capability of the device. This, in combination with overshoot when tracking fast changes, might have resulted in some large spikes that can be seen.

Effects of Modeling Errors

Simulation results indicate that the nonlinear disturbance observer can be a good candidate for implementing closed loop force control of haptic interfaces in the absence of a force sensor mounted on the device. It should be noted however that the accuracy of the estimation is dependent upon the robot model employed. Specifically, any errors in robot model would appear as a part of force estimates from the disturbance observer. Referring to Figure 3, if $\Delta\mathbf{F}$ be the error in force estimation, we have

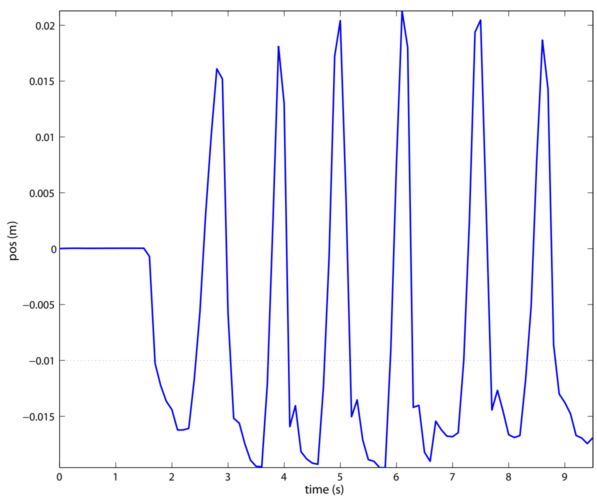

Figure 7. Virtual wall interaction under impedance control with force feedback, Kf = 0.1

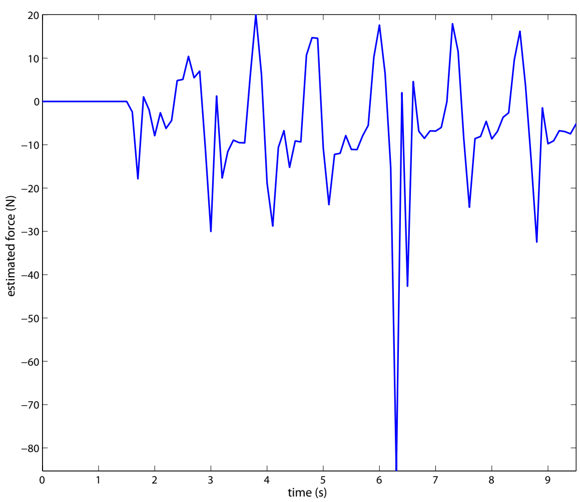

Figure 8. Virtual wall interaction under impedance control with force feedback (estimated contact forces)

$$\mathbf{x} = \mathbf{Z}_m^{-1}(\mathbf{F} - \mathbf{Z}_h\mathbf{x} - \mathbf{Z}_e\mathbf{x} \\ + K_f(\mathbf{F} - \mathbf{Z}_h x + \Delta\mathbf{F} - \mathbf{Z}_e\mathbf{x})) \quad (20)$$

$$\left(\frac{\mathbf{Z}_m}{1+K_f} + Z_e + Z_h\right)\mathbf{x} = \mathbf{F} + K_f\frac{\Delta\mathbf{F}}{1+K_f} \quad (21)$$

$$\frac{\mathbf{x}}{F} = \left[1 + \frac{K_f\Delta\mathbf{F}}{\mathbf{F}(1+K_f)}\right]\frac{1}{\frac{\mathbf{Z}_m}{1+K_f} + Z_e + Z_h} \quad (22)$$

Hence, as compared to the the case of no modeling errors, the impedance felt by the user, as defined by Equation (5) is scaled by a factor of $1/(1+\frac{\Delta\mathbf{F}}{\mathbf{F}}\frac{K_f}{1+K_f})$. For large K_f, this becomes $1/(1+\frac{\Delta\mathbf{F}}{\mathbf{F}})$. The impedance felt by the user is then smaller than the desired impedance if forces are underestimated by the observer ($\Delta\mathbf{F} > 0$) and vice versa if forces are overestimated.

CONCLUSIONS

A control scheme for sensorless closed loop control of a haptic interface has been presented in this paper. The proposed observer was tested in simulation. Although the observer is designed for constant disturbances, it performs satisfactorily for continuously changing forces. Simulation and experimental results indicate that the observer can be used in place of a force sensor for closed loop impedance control of a haptic interface. As any observer, however, the proposed approach is susceptible to modeling errors. Specifically, the relative error in the displayed impedance is found to be inversely proportional to $1+\Delta\mathbf{F}/\mathbf{F}$ for large force gains.

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