Disturbance-Observer-Based Force Estimation for Haptic Feedback

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In this paper, we propose the use of a nonlinear disturbance-observer for estimation of contact forces during haptic interactions. Most commonly used impedance-type haptic interfaces employ open-loop force control under the assumption of pseudostatic interactions. Advanced force control in such interfaces can increase simulation fidelity through improvement of the transparency of the device. 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. Using a disturbance-observer, we estimate contact forces at the tool tip, then use these estimates for closed-loop control of the haptic interface. Simulation and experimental results, utilizing a custom single degree-of-freedom haptic interface, are presented to demonstrate the efficacy of the proposed disturbance-observer (DO)-based control approach. This approach circumvents the traditional drawbacks of force sensing while exhibiting the advantages of closed-loop force control in haptic devices. Results show that the proposed disturbance-observer can reliably estimate contact forces at the human-robot interface. The DO-based control approach is experimentally shown to improve haptic interface fidelity over a purely open-loop display while maintaining stable and vibration-free interactions between the human user and virtual environment. [DOI: 10.1115/1.4001274]

1 Introduction

Haptic displays enable force feedback from virtual environments, a feature that can enhance the sensation of immersion in the simulated world. The quality of the haptic simulation, when considered from the perspective of device performance, is often termed fidelity or transparency, and is characterized by the level of impedance discrimination that can be detected at the interface [1]. 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. The fidelity of interface can be improved through optimized design of the robotic interface and via active control. Note that fidelity is a measure of the performance of a control algorithm rather than an indicator of the perceived realism of the virtual environment. The "realism" of the haptic display refers to how closely the displayed virtual environment matches the real system being simulated, and is dependent on both the haptic rendering and control algorithms chosen by the developer.

The effect of device dynamics can be minimized through careful design choices. For example, low force output devices can be designed to have negligible dynamic properties with the use of efficient drive trains (cable, harmonic drives) and high strength-to-weight materials. Counterbalancing can also be used to remove gravitational effects although at the cost of increased inertia, thereby, negating the effectiveness of the above techniques. Ellis et al. [2] discussed the effect of various design parameters on performance through the design of a three degree-of-freedom (DOF) haptic interface. Gupta and O'Malley [3] provided a similar discussion of factors involved in the design of exoskeletal interfaces. When larger force output is desired, it becomes increasingly difficult to passively reduce the dynamic effects of manipulator dynamics. High force output devices require the 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 reduce the fidelity required for display of details in the environment, thus degrading human performance of dexterous tasks.

Active control is needed to reduce the perceived haptic device dynamics beyond what is achievable through design alone. Several techniques are commonly used with haptic interfaces such as model feed-forward control, loop-shaping techniques, or closed-loop (CL) force feedback; however, there are limitations with each approach.

Model feed-forward control can improve performance; however, this approach is very susceptible to modeling errors, and is most effective for compensation of gravity and friction effects rather than inertia compensation [1]. Some researchers have investigated the use of "loop-shaping" techniques for improvement of performance and stability for haptics and bilateral teleoperation [4–6]. In these works, linear time invariant models of the robot and human were employed for controller design. Nonlinearities associated with the robot can significantly affect the behavior of these controllers away from the nominal operating point. Additionally, human subjects exhibit significant variations, and separate models are required for different users [7].

Closed-loop force feedback controllers are another potential solution for reducing device dynamics [1]; however, the use of force and torque sensors in haptic devices is limited due to stability, inertia and cost considerations. During force control, robots often become unstable during contact with stiff environments. For example, a study by An and Hollerbach [8] analyzed the dynamic stability of a system through simple robot and environment models. The results of the study indicate that the unmodeled high frequency dynamics in the robotic system and the environmental stiffnesses affected the stability of the robot in contact with the environment.

Other limitations are imposed by the implementation requirements of closed-loop force control, namely, the need for direct sensing of the end point forces. Katsura et al. [9] note that the limited bandwidth and high cost of force sensors hinder their widespread acceptance for such applications. The force sensor employs a strain gauge and thus 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's response. Instead, Katsura et al. proposed 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. A disturbance-observer-based sensorless torque control approach was also presented by Murakami et al. [10]. Zahn et al. [11] explored the use of neural networks for friction estimation for sensorless force control of manipulators. Such neural-network based approaches are not suitable for haptic displays, as the nature of contact forces change with display impedances. A neural-network used to track these forces would then need to be trained again.

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In this work, we propose the use of a nonlinear disturbance-observer for estimation of contact forces during haptic interactions. The method presented in this paper requires no additional modeling or computation as is required in Katsura et al. [9]. Our approach circumvents the traditional drawbacks of force sensing while incorporating the advantages of closed-loop force control in haptic devices. The exponential convergence of nonlinear disturbance-observer for constant disturbances is also shown. Traditionally, a disturbance-observer-based control approach involves designing an observer to estimate external disturbances and then compensating for the influence of the disturbance. A second controller is then used to achieve the control objectives. In comparison, in this work the nonlinear observer is used to estimate contact forces that are used for feedback during controller design. However, due to the similarity in the structure of the proposed controller and traditional disturbance-observers the terminology "disturbance-observer-based control" is employed.

The remainder of the paper is organized as follows. The nonlinear disturbance-observer design is presented in Sec. 2. In Sec. 3, we present our experimental setup and in Sec. 4, experimental results, which demonstrate the applicability of disturbance-observer base force estimation to closed-loop haptic control are presented.

2 Nonlinear Disturbance Observer

In this section, we present the design of the nonlinear disturbance-observer. The model of an n-link robot manipulator can be written as

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \mathbf{T} + \mathbf{d} \tag{1}$$

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.

Chen et al. [12] outlined a generic approach to nonlinear disturbance-observer design through the use of an auxiliary variable. Following the approach presented in Chen et al. [12], we define an auxiliary variable vector

$$\mathbf{z} = \hat{\mathbf{d}} - \mathbf{p}(\mathbf{q},\dot{\mathbf{q}}) \tag{2}$$

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, we define a nonlinear function $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})$ such that

$$\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} = \frac{\mathrm{d}\mathbf{p}(\mathbf{q},\dot{\mathbf{q}})}{\mathrm{d}t} \tag{3}$$

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

$$\dot{\hat{\mathbf{d}}} = -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\hat{\mathbf{d}} - \mathbf{d}) \tag{4}$$

Differentiating Eq. (2) gives

$$\dot{\mathbf{z}} = -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{z} + \mathbf{p}(\mathbf{q},\dot{\mathbf{q}})) + \mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) - \mathbf{T})$$
$$-\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{D}(q)\ddot{\mathbf{q}} \tag{5}$$

$$= -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{z} + \mathbf{L}(\mathbf{q},\dot{\mathbf{q}})(\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) \tag{6}$$

$$-\mathbf{T} - \mathbf{p}(\mathbf{q},\dot{\mathbf{q}})) \tag{7}$$

The error in force estimation is then given by

$$\mathbf{e} = \mathbf{d} - \hat{\mathbf{d}} \tag{8}$$

Since no prior information about the disturbance is available, we assume that $\dot{\mathbf{d}}=0$. Then differentiating Eq. (8), we have

$$\dot{\mathbf{e}} = \dot{\mathbf{d}} - \dot{\hat{\mathbf{d}}} \tag{9}$$

$$= -\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})\mathbf{e} \tag{10}$$

Hence, the estimation $\hat{\mathbf{d}}$ converges to $\mathbf{d}$ if the function $\mathbf{L}(\mathbf{q},\dot{\mathbf{q}})$ is such that Eq. (10) 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 Eq. (3) satisfies the stability condition for Eq. (10). 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. Hence, we choose

$$\mathbf{p}(\mathbf{q},\dot{\mathbf{q}}) = c\dot{\mathbf{q}} \tag{11}$$

Using Eq. (3), we now have

$$L(\mathbf{q},\dot{\mathbf{q}}) = c\mathbf{D}^{-1}(\mathbf{q}) \tag{12}$$

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 [13]. As a result, Eq. (10) is exponentially stable.

Next, we define a Lyapunov function candidate

$$V(\mathbf{e}) = \frac{1}{2}\mathbf{e}^{\mathrm{T}}\mathbf{e} \tag{13}$$

Differentiating Eq. (13) along the observer trajectory gives

$$\dot{V}(\mathbf{e}) = -c\mathbf{e}^{\mathrm{T}}\mathbf{D}^{-1}(\mathbf{q})\mathbf{e} \tag{14}$$

Note that $\mathrm{d}V(\mathbf{e})/\mathrm{d}t < 0, \forall \mathbf{e}, t$ due to the positive definiteness of the inverse of the inertia matrix. Hence, Eq. (10) is exponentially stable and the rate of convergence is proportional to c.

3 Methods

The proposed disturbance-observer is employed as a means of sensing forces, thereby, enabling closed-loop control of haptic interfaces without the typical negative effects of sensor-actuator noncollocation. For this approach, we assume that the forces exerted by the human operator are the only external forces acting on the device. Experiments to test the use of the disturbance-observer as a means of sensing forces were conducted with a custom single degree-of-freedom haptic interface. Additionally, in order to investigate the feasibility of disturbance-observer-based control for haptic feedback, we measure the transparency bandwidth of the single degree-of-freedom interface under open, closed, and disturbance-observer-based controllers.

3.1 Setup. The experimental apparatus consists of a low-cost one degree-of-freedom custom built impedance display type haptic device that displays forces on a palm grip handle, as shown in Fig. 1. The handle assembly is driven by a cable-and-pulley drive system and translates on a ball-slider. A position encoder and an accelerometer are mounted on the handle assembly to measure the handle's instantaneous states, which are used to render interaction forces characterizing the virtual dynamical system. An ATI nano-17 force sensor is mounted on the handle assembly to measure interaction forces. The force sensor is only used to measure interaction forces for the closed-loop force control condition, and is not required for the proposed method of force estimation via the disturbance-observer-based control. The haptic interface has a workspace of approximately 0.15 m and the maximum continuous force output of 4 N.

The device is interfaced with the control computer through the Q8 data acquisition board from Quanser Inc. Control of the haptic interface was implemented using the MATLAB real-time workshop. An update rate of 1000 Hz was used for all experiments.

3.2 System Modeling. The device was modeled as a simple mass acted on by friction in addition to the motor torques. Friction was modeled as a combination of Coulomb and viscous friction.

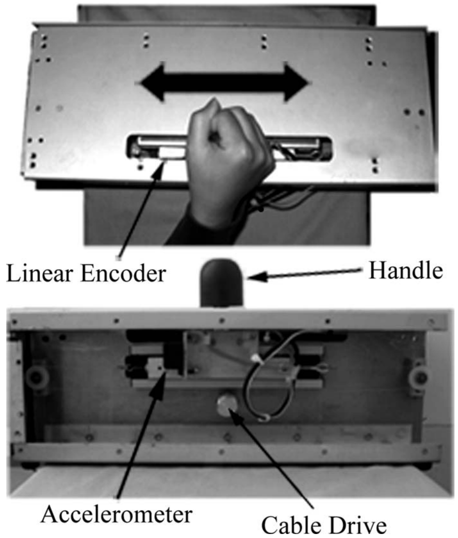


Fig. 1 Single degree-of-freedom haptic interface

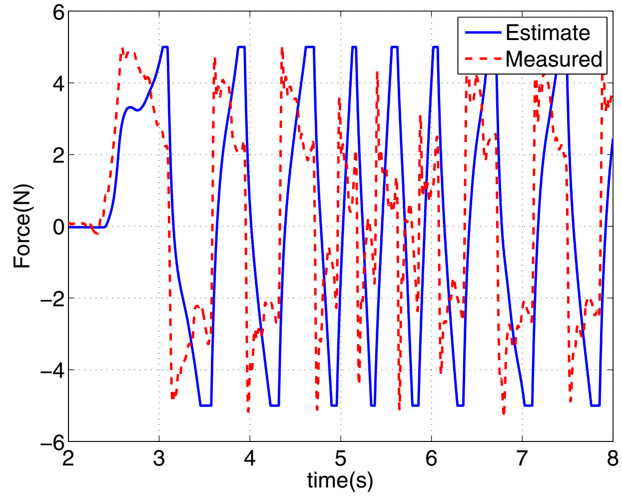


Fig. 3 Measured (dashed) and estimated (solid) contact forces during virtual wall interaction (*K*=800 N/m)

The stiffness of the cable transmission was omitted from the model as its contribution to forces acting on the mass was negligible as compared with the frictional terms. The equation of motion of the device is thus given by

$$m\ddot{x} + c\dot{x} + F_c \,\mathrm{sgn}(\dot{x}) = \tau \tag{15}$$

where x is the position of the device, m is the mass, c is the viscous friction coefficient, F_c is the Coulomb friction, and τ is the motor torque. The system parameter values as identified were: mass, $m=0.416$ Kg; viscous damping coefficient, $c=1.272$ Ns/m; and Coulomb friction, $F_c=0.24$ N

4 Results

Figures 2 and 3 show the comparison of the measured and estimated contact forces during free movement, and interaction with a virtual wall, respectively. Forces estimated using the disturbance-observer are depicted with solid lines, whereas the values as measured using the force sensor are shown using dashed lines. The virtual wall was simulated as a simple spring of stiffness 800 N/m. The disturbance-observer output was limited to ± 4 N to match the continuous force output of the device during the virtual wall simulation. We find that the disturbance-observer tracks the contact forces between the user and the device with slight time delay. Mismatch between the estimated and measured forces is maximum near the peaks. This is an expected result due to the high rate of change in forces near the peak, and the fact that the observer was designed to track piecewise constant forces. The errors observed in force estimation are larger during virtual wall interaction when compared with free movement. This difference could be due to saturation effects in the motor as the maximum force output of the device is limited to 4 N. The behavior of the motor near maximum force output is not modeled in the observer, which employs the commanded motor torques (current) for force estimation. Hence, it is possible that while the observer assumes that the motor tracks the commanded torques perfectly, in reality that might not be the case. This is also reflected in the fact that in the ± 3 N range is almost comparable in the two cases.

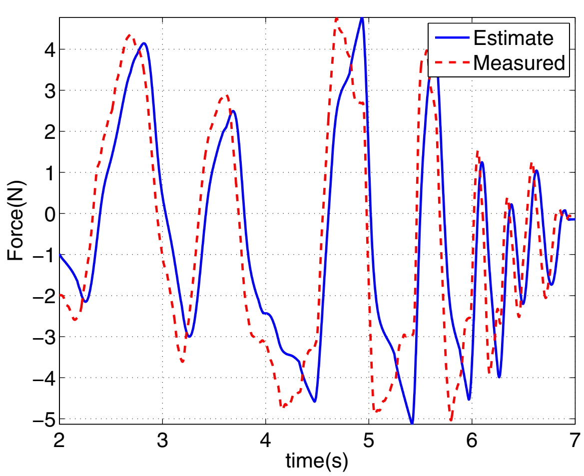
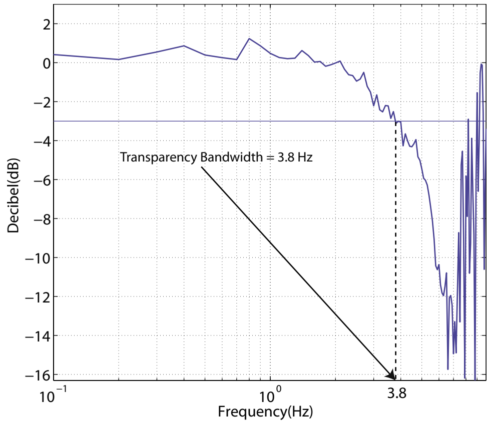


Fig. 2 Measured (dashed) and estimated (solid) contact forces during free space interaction

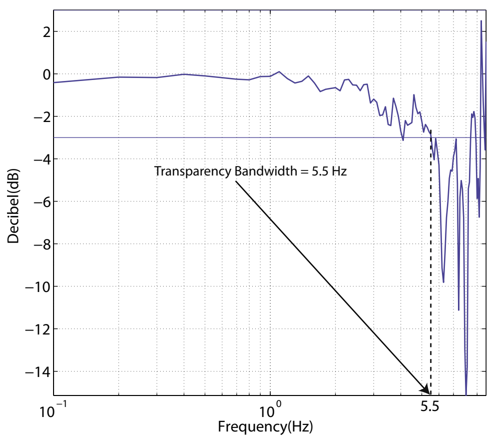
Stability and performance of disturbance-observer-based haptic feedback was compared with that of traditional open- and closed-loop controllers experimentally using the single DOF device. The setup for these experiments was the same as previously described in Sec. 3.

During the experiment to characterize the stability of the interface, a single male user attempted to generate sustained vibrations of the haptic device against a virtual wall. A similar approach was adopted by Abbott and Okamura [14] and Diolaiti et al. [15] to investigate virtual wall behavior. Three different controllers—an open-loop (OL) impedance controller, a closed-loop impedance controller, and a disturbance-observer-based closed-loop controller—were tested at wall stiffness values of 800 N/m, 1600 N/m, 2400 N/m, and 3200 N/m. It was found that for the three controllers—the (OL) controller, the (CL) controller with a force gain of 2, and the DO-based controller—the sustained vibrations appeared at wall stiffness values of 2400 N/m, 800 N/m, and 3200 N/m, respectively.

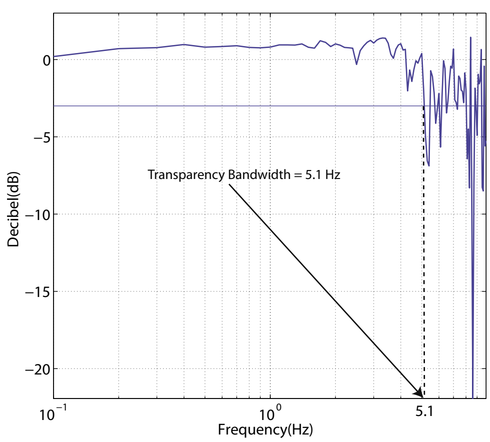
The fidelity of the haptic interface was measured in terms of its transparency bandwidth, which is a measure of the range of frequencies of forces that can be displayed with the haptic interface. Transparency bandwidth of the haptic interface during the display of a virtual wall of stiffness 800 N/m was also compared for the open-loop, closed-loop and disturbance-observer-based controllers. For the transparency characterization, the highest value of the force gain, which did not result in unwanted vibrations, was chosen for the closed-loop controller. As the disturbance-observer-based controller had a vibration-free response over a wider range of force gains, a low force gain value of 1 was chosen as increasing this gain improves performance. Following the approach adopted by Fite et al. [16], the transmitted impedance, $\mathbf{Z}_{cl}$ was estimated as a function of frequency by dividing the cross spectral



(a) OL controller



(b) CL controller, $K_f = 2$



(c) DO Controller, $K_f = 1$

Fig. 4 Transparency bandwidth for (*a*) open-loop, (*b*) closed-loop, and (*c*) disturbance-observer based controllers (wall stiffness=800 N/m)

density between the motion input and force output by the power spectral density of the motion input. The transparency transfer function can then be computed using the desired impedance values. The following relationships was used for the computations:

$$\mathbf{Z}_{cl}(j\omega) = \frac{\Phi_{VF}(j\omega)}{\Phi_{VV}(j\omega)} \tag{16}$$

where $\Phi_{VF}(j\omega)$ is the cross spectral density between the motion and force and $\Phi_{VV}(j\omega)$ is the power spectral density of the motion input.

The transparency transfer function is computed by dividing the transmitted impedance $\mathbf{Z}_{cl}$ by the desired impedance $\mathbf{Z}_d$. The transparency bandwidth for the OL, CL, and DO controllers was found to be 3.8 Hz, 5.5 Hz, and 5.1 Hz, respectively, as shown in Fig. 4.

5 Conclusions

A nonlinear disturbance-observer for estimation of external joint torques acting on the robot manipulator has been presented. The observer was tested through experiments. Although the observer is designed for constant disturbances, it performs satisfactorily for continuously varying forces. Results indicate that the observer can be used in place of a force sensor for closed-loop impedance control of a haptic interface. The use of a disturbance-observer in lieu of a noncollocated force sensor can help improve stability of haptic interactions under closed-loop control. It should be noted that in a real-world situation, exponential stability in presence of constant disturbances, as predicted by the analysis in this work, is not possible owing to changes in external force and modeling errors. These issues regarding the stability of the observer will be investigated in the future.

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