Adjusting Output-Limiter for Stable Haptic Interaction with Deformable Objects

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Abstract—This paper presents a control method using an adjusting output-limiter for stable haptic rendering in a virtual environment. In a simulation of force-reflecting interaction with deformable objects in a virtual environment, a quick computation of the accurate impedance of deformable objects is rare. This is particularly true when physics-based models, such as tensor-mass models or mass-spring models, are used. The problem is aggravated if the simulation involves changes in the geometry and/or impedance of the deformation model, such as cutting or suturing. The proposed control method guarantees stable haptic interactions with deformable objects of unknown and/or varying impedance. The method is based on the time-domain passivity theorem and the two-port network model. The controller adjusts the maximum permissible force to guarantee the passivity of the haptic system at every sampling instant. The controller notes only the magnitude of the reflective force, and does not depend on properties of the employed force model. This allows the proposed control method applicable to haptic systems involving deformable objects with unknown, nonlinear, and/or time-varying impedance. Designs of the controllers are presented for impedance-type and admittance-type haptic systems. The method is also extended for multiple degrees-of-freedom.

Keywords: Haptic control; Haptic rendering; Passivity

I. INTRODUCTION

Multimodal interaction involving haptic and visual feedback enhances the fidelity and experience of the simulation in a virtual environment. It is important in haptic rendering to generate a realistic reflective force in real time. Medical simulation [1], [2] often requires physics-based deformation models such as finite-element models and mass-spring models to display realistic deformation and reflective force. Estimation methods [3], [4], [5] exploiting previous positions and forces are used for real-time computation of a reflective force, due to the low update rate that results from the computational complexity of the deformation model. Estimation error can jeopardize the stability of the haptic system. Moreover, the impedance of the deformation model is comparatively small, nonlinear, time-varying and often unknown. It is difficult to compute accurate impedance values for deformable objects in real time. This problem is magnified if the simulation involves changes in the geometry and/or impedance of the deformation model, such as cutting or suturing. Hence, it is difficult to guarantee the stable haptic interactions with the deformation model. The controller is necessary to maintain the fidelity of the reflective force while guaranteeing the stability.

Barbagli et al. [6] described an adaptive local haptic model that allowed users to interact haptically with a deformable object simulation featuring computational delays and low servo rates. Asymptotic stability is guaranteed when the stiffness of the local haptic model is smaller than that of the deformable object at a contact point; however, it is necessary for the real stiffness of deformable objects to be estimated. Mahvash and Hayward [7] propose a passivity condition considering the combined effects of zero-order-hold and computational delay. The passive-force response is synthesized from the local force fields and the passivity condition. It can be applied when the impedance of the deformable object is known beforehand.

Control methods based on a virtual coupling [8], [9] can guarantee the stable haptic interaction with a rigid body, regardless of the impedance of a rigid object. However, the virtual coupling cannot decouple an operator from a virtual environment when the impedance of the virtual environment is small. It hinders the operator from feeling realistic impedance from the deformation model, which degrades the fidelity of the reflective force. Hannaford and Ryu [10] employ a time-domain passivity strategy that has the potential to generate a large impulse. Time-domain passivity control with reference energy following [11] is proposed to make the output of the passivity controller smooth. It is difficult to compute the correct reference energy because the update rate of the physics-based deformation model is low and the correct reflective force is unknown during the intersample period. Stramigioli et al. [12] propose a port-Hamiltonian approach to track and dissipate energy excess, but it is not clear how it can be applied to nonlinear multidimensional virtual environments. The energy bounding algorithm [13] makes the system stable, regardless of the range of the impedance and the sampling frequency; however, it deteriorates the fidelity of the reflective force, because it controls the reflective force computed from the physics-based deformation model at every sampling instant.

An adjusting output-limiter (AOL) is presented in this paper for stable force-reflection in virtual environments. The AOL is developed based on the passivity theorem and on a two-port network model. It monitors the maximum permissible force to guarantee the passivity of the haptic system at every sampling instant. In addition, the AOL adjusts the reflective force for the passivity while sacrificing the fidelity of the reflective force only if the force computed from the deformation model is larger than the maximum permissible force. Otherwise, the high fidelity of the reflective force is maintained. The AOL can maintain the stability of the haptic system regardless of
the unknown, nonlinear, and/or time-varying impedance of a deformable object. It creates a stable haptic system even when large impulses or discontinuous reflective forces that can arise from estimation errors are generated. An adjusting output-limiter for an impedance or admittance-type haptic system is presented here. It is extended for the haptic system with multiple degrees-of-freedom. The efficacy of the controller is shown through experiments.

II. ADJUSTING OUTPUT-LIMITER

Fidelity is the ability of a simulator to simulate real-world interactions. It is assumed that the deformation and the reflective force from a virtual environment are sufficiently realistic. The fidelity measure of a reflective force is defined as the difference between the reflective force transmitted to the operator and the force computed from a physics-based deformation model. This implies that the smaller the difference, the higher the fidelity.

The adjusting output-limiter (AOL) observes the maximum permissible force to guarantee passivity of the haptic system at each sampling period, as shown in Fig. 1(a). As shown in Fig. 1(b), the AOL adjusts the reflective force while sacrificing the fidelity of the reflective force, only if the force computed from the deformation model is larger than the maximum permissible force. Otherwise, the high fidelity of the reflective force is maintained, while guaranteeing the passivity of the system.

The AOL is based on time-domain passivity theories. It takes the sample-and-hold (ZOH) effect into account. The energy generated by the ZOH and computational time-delay, as well as energy dissipated by viscous and Coulomb friction of the haptic device, are all monitored at every sampling instant. The maximum energy generated at the next sampling instant is predicted, and the AOL controls the maximum permissible force to maintain stable haptic rendering in the virtual environment.

The bilateral reflective force in a two-port network model of the impedance-type haptic system is considered, as shown in Fig. 2. The human operator is assumed to be passive. Energy in the haptic device at sampling instant \( kT \), \( E(kT) \), is derived as shown in (1), using

\[
E(kT) = \int_{kT}^{(k+1)T} \left[ M_d v_d^2(t) + B_d v_d(t) \right] dt + \int_{kT}^{(k+1)T} \left[ f_\text{cond} v(t) + f_p v(t) \right] dt
\]

\[
= \frac{1}{2} M_d v_d^2(kT) + B_d \sum_{n=0}^{k} v_d^2(nT) dt + \int_{kT}^{(k+1)T} f_\text{cond} v(t) dt + \int_{kT}^{(k+1)T} f_p v(t) dt
\]

\[
\geq B_d^{\text{min}} \cdot T \cdot \sum_{n=0}^{k} v_d(nT) + f_\text{cond} \cdot T \cdot \sum_{n=0}^{k} v_d(nT) + f_p \cdot T \cdot \sum_{n=0}^{k} v_d(nT)
\]

(1)

where \( f_\text{cond} \) and \( B_d^{\text{min}} \) are defined as the minimum of the Coulomb and the viscous friction at all positions, respectively, which are assumed to be constant.

The reflective force \( f_p(k) \) is controlled to satisfy the condition \( E(kT) \geq 0 \) for \( \forall v_d(kT) \). The velocity to minimize \( E(kT) \), \( v_d(kT)_{\text{min}(E(kT))} \), is derived from differentiating (4); this is a function of the sign of \( v_d(kT) \) and the range of the reflective force, \( f_p(k) \), as

\[
E(kT) = \sum_{n=0}^{k} f_p(nT) v_d(nT) dt + \sum_{n=0}^{k} f_\text{cond}(nT) v_d(nT) dt
\]

\[
= T \cdot \sum_{n=0}^{k} f_p(nT) v_d(nT) + T \cdot \sum_{n=0}^{k} f_\text{cond}(nT) v_d(nT)
\]

\[
\geq B_d^{\text{min}} \cdot T \cdot \sum_{n=0}^{k} v_d(nT) + f_\text{cond} \cdot T \cdot \sum_{n=0}^{k} v_d(nT)
\]

(2)

(3)

(4)

(5)
shown in (5). Four cases are considered according to the sign of \( v_d(k+1) \) and the range of \( f_p(k) \), as shown in TABLE I.

### TABLE I. Four Cases To Compute The Range of \( f_p(k) \) That Satisfies \( E(k+1) \geq 0 \)

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
<th>( f_p(k) ) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>( v_d(k+1) \geq 0 ) and ( f_p(k) + F_{\text{min,cool}} \geq 0 )</td>
<td>(-\frac{1}{2} f_p(k) + F_{\text{min,cool}} \geq 0 )</td>
</tr>
<tr>
<td>Case II</td>
<td>( v_d(k+1) \leq 0 ) and ( f_p(k) - F_{\text{min,cool}} \geq 0 )</td>
<td>(-\frac{1}{2} f_p(k) - F_{\text{min,cool}} \geq 0 )</td>
</tr>
<tr>
<td>Case III</td>
<td>( v_d(k+1) \geq 0 ) and ( f_p(k) + F_{\text{min,cool}} &lt; 0 )</td>
<td>(-\frac{1}{2} f_p(k) + F_{\text{min,cool}} &lt; 0 )</td>
</tr>
<tr>
<td>Case IV</td>
<td>( v_d(k+1) \leq 0 ) and ( f_p(k) - F_{\text{min,cool}} &lt; 0 )</td>
<td>(-\frac{1}{2} f_p(k) - F_{\text{min,cool}} &lt; 0 )</td>
</tr>
</tbody>
</table>

The velocity to minimize \( E(k+1) \) in (4) under the condition \( v_d(k+1) \geq 0 \), \( v_d(k+1)_{\text{min}} \), becomes zero, as \( E(k+1) \) is a second-order function of \( v_d(k+1) \) and the coefficient of \( v_d(k+1)^2 \) is positive. When \( v_d(k+1) \) is zero, \( E(k+1) \) becomes non-negative, that is, the system is passive regardless of the value of \( f_p(k) \). Hence, the system becomes passive at the \((k+1)T\) instant if \( f_p(k) \geq -F_{\text{min,cool}} \).

### Adjusting Output-Limiter:

If \( f_p(k) \geq f_p(\kappa)_{\text{max}} \), then \( f_p(k) = \text{sgn}(f_p(\kappa)) \cdot f_p(\kappa)_{\text{max}} \) \( f_p(\kappa) = f_p(\kappa) \)

where \( f_p(\kappa)_{\text{max}} = F_{\text{min,cool}} + \sqrt{4B_d^2 \cdot [E'(k)]^T} \).

The controller notes only the magnitude of the reflective force regardless of properties of the reflective-force model. Hence, the controller guarantees stable haptic interactions even when impedance of the virtual environment is unknown, time-varying, and/or nonlinear. The controller can be also used when the sampling rate is low and/or a time-delay exists.

### A. Adjusting Output-Limiter for Admittance-Type Haptic Systems

In an admittance-type interaction, the displacement is generated in response to the measured force while the force is generated in response to the measured displacement in an impedance-type haptic system. Adams [8] derived such an admittance-type haptic display by adding a proportional-integral (PI) velocity control loop, \( f_r^* = K_{rI}(z) \cdot [v_d^* - v_d] \), to the impedance-type interaction model, in which \( f_r^* \), \( v_d^* \), \( v_d \), \( K_{rI}(z) \) are the force of actuation, the velocity of the haptic device, the commanded velocity, and the PI-controller, respectively. A two-port network model for an admittance-type haptic system is designed as shown in Fig. 3. The force applied by the human operator, \( f_h^* \), and the velocity of the haptic device, \( v_d(k) \), can be measured at a high rate. The desired velocity, \( \hat{v}_d(k) \), in response to input \( f_h^* \) is computed from...
the admittance-type deformation model. The commanded force, \( f_c(k) \), is determined by the PI-velocity controller, and the AOL adjusts the commanded force to make the system passive. Hence, the two-port network model for the admittance-type haptic system is equivalent to the model for the impedance-type haptic system. The energy for each sub-system in the admittance-type haptic system can be computed using procedures identical to those of the impedance-type haptic system. The AOL in (6) can be applied to the admittance-type haptic system by substituting the commanded force, \( f_c(k) \), for the reflective force, \( f_r(k) \). While the AOL adjusts the reflective force from the deformation model, \( f_r(k) \), in the impedance-type haptic system, it adjusts the commanded force, \( f_c(k) \), in the admittance-type haptic system.

### B. Adjusting Output-Limiter for Haptic Systems with Multiple Degrees-of-Freedom

The total energy of the haptic system can be computed from (7) when the system is p-d.o.f. [14]. The AOL can be extended straightforwardly for a haptic system with multiple degrees-of-freedom using (7). \( E_i(k), B_{d,i}^{min}, f_{pd,i}^{min}, v_{y,i}, f_{c,i} \) and \( f_{r,i} \) are the energy, minimum viscous and Coulomb friction, velocity and the reflective force at the sampling instant \( kT \) for the \( i \)-directional motion, respectively. The total energy of the system becomes non-negative if the energy for each d.o.f. is non-negative; that is, if \( E(k) \geq 0 \). Each controller for the \( i \)-directional motion makes the total energy non-negative.

\[
E(n) = \sum_{k=0}^{n} f_i^{2}(k)\dot{v}_i(k)\cdot T = \sum_{k=0}^{n} \left( \sum_{i=1}^{p} f_i(k)v_i(k)\right) \cdot T = \sum_{k=0}^{n} \left( \sum_{i=1}^{p} E_i(k) \right) \tag{7}
\]

where, \( E_i(k) = B_{d,i}^{min} \cdot T \cdot \sum_{n=0}^{k \cdot T} v_{y,i}(n+1)^2 \)

\[+ f_{pd,i}^{min} \cdot T \cdot \sum_{n=0}^{k \cdot T} f_{r,i}(n+1) + T \cdot \sum_{n=0}^{k \cdot T} f_{c,i}(n)v_{y,i}(n+1) \]

### III. EXPERIMENTS AND RESULTS

The AOL is experimented using a 6-d.o.f. haptic device, PHANToM. The Coulomb and viscous frictions of the PHANToM are measured using the friction measurement procedure developed by Kelly [15]. The Coulomb and viscous frictions are computed from (8) and (9), where the mass of PHANToM, \( J \), is set at 0.075 Kg. The parameter \( a \) is the slope of the velocity curve over time, and \( b/a \) is the intersection with the time axis. The coefficient of frictions of PHANToM varies according to the position. The frictions are measured at five different positions for each axis. The velocity responses to a force ramp input with slope \( m \) (N/s) are measured more than five times at each position to average out any stochastic influence. The minimum frictions at each axis are then chosen, as shown in TABLE II.

\[
\text{Coulomb friction: } f_c = \frac{b}{a} - m - a \cdot J. \tag{8}
\]

\[
\text{Viscous friction: } f_v = \frac{m}{a}. \tag{9}
\]

Five different experiments are designed to show the efficacy of the AOL. The AOL is applied to a 1-d.o.f. motion. The frictions at the x-axis in TABLE II are used. These cases include when the impedance of the deformation model is unknown, very large, time-varying, and/or nonlinear as shown in TABLE III. The effects of a low sampling rate and a large time-delay are also investigated. The sampling rate of the experiments is set to 1 kHz with the exception of experiment D. The contact node is pulled and pushed repeatedly, as shown in Fig. 4 (a), and the reflective force from the designed force model is generated. Fig. 4(b) shows the desired response. The magnitudes of the impedance of the five force models in TABLE III are not the maximum allowable impedance. The proposed control method makes the system stable even if the impedance of the virtual model becomes larger than in the five experiments.

<table>
<thead>
<tr>
<th>TABLE II. MEASURED FRICTIONS OF PHANTOM</th>
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<tbody>
<tr>
<td>X-axis</td>
</tr>
<tr>
<td>Coulomb friction (N), ( F_{c,\text{min}}^{\text{min}} )</td>
</tr>
<tr>
<td>Viscous friction (Ns/m), ( B_{d,i}^{\text{min}} )</td>
</tr>
</tbody>
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<tr>
<th>TABLE III. EXPERIMENTAL CONDITIONS OF THE EXPERIMENTS</th>
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<tbody>
<tr>
<td>F=force (N), ( \Delta \text{x}=\text{displacement (mm), } t=\text{time} )</td>
</tr>
<tr>
<td>Experiments (condition)</td>
</tr>
<tr>
<td>A (Time-varying)</td>
</tr>
<tr>
<td>B (Nonlinear)</td>
</tr>
<tr>
<td>C (Large time-delay) without control:</td>
</tr>
<tr>
<td>C (Large time-delay) with control:</td>
</tr>
<tr>
<td>D (Low sampling rate)</td>
</tr>
<tr>
<td>E (Large stiffness)</td>
</tr>
</tbody>
</table>
The system becomes unstable without control in all five experiments, as shown by the left column of Fig. 5. The results of application of the AOL are shown in the right column of Fig. 5. The operator can move as planned, which is a benefit of the AOL. The circles A and B in Figs. 5(a) and (b) represent high-frequency oscillations. The operational stiffness is defined as $K_{\text{operation}} = (F_k - F_0)/(x_k - x_0)$ in which $x_0$, $F_0$, $x_k$, and $F_k$ are the initial and the $k$-th measured positions, along with the corresponding forces, respectively. The operational stiffness measurements of the experiments A and B are approximately 530 N/m and 530 N/m, respectively. The AOL depends only on the magnitude of the current reflective force; hence, the proposed control method makes the system stable even when the time-delay is quite large or when the sampling rate is low, as shown in Figs. 5(c) and (d). The operational stiffness measurement in the experiments C and D are approximately 180 N/m and 16 N/m, respectively. It is important to note that the stiffness in the experiment D is one third of that of the experiments A and B. The operational stiffness in experiment E is approximately 500 – 600 N/m while the stiffness of the virtual model is 4000 N/m. This results because the AOL limits magnitude of the reflective force to maintain the passivity.

Another force model with time-varying impedance, $F = 5000(N/m)s*[\sin (t/sec)]*\Delta x$, is introduced to show how the AOL maintains the fidelity of the reflective force. Once the impedance of the force model is increased, however, it is decreased again. This is done repeatedly. The impedance of the employed force model changes and the corresponding reflective force varies as shown in Fig. 6. The solid line indicates the force computed from the force model and the solid line with ‘pentagram’ is the force controlled by the AOL in Fig. 6(a). The AOL controls the force only if the force computed from the deformation model is larger than the maximum permissible force, as shown in Fig. 6(a). Otherwise, a reflective force with high fidelity is generated. The reflective force from 3.054 sec to 3.190 sec is generated without adjustment of the AOL, as shown in Fig. 6(b). The adjusting output-limiter (AOL) monitors the output force from the controller and the line with the ‘pentagram’ indicates the estimated force in Fig. 6(a). The correct output force computed from the deformation model is used for the estimation model [4], and $F = 2*10^4(N/mm^3)*\Delta x^3$ is used for the reflective force model. The input displacement is measured at 1 kHz and the output force is computed at 25 Hz from the deformation model. The computational time-delay is assumed to be 40 ms. The P-matrix is reset whenever $\phi(k - 1)J^T P(k - 2)J\phi(k - 1) < 0.8$. The contact node is pulled and pushed repeatedly, as shown in Fig. 4.

When the estimation error is small, the interaction with the deformation model is stable. However, a large estimation error is often generated, as shown in Fig. 7(a). The solid line represents the force computed from the deformation model, and the line marked with the ‘pentagram’ indicates the estimated force in Fig. 7(a). The correct output force computed from the deformation model is two thirds of the estimated output force. The estimation error is larger than 4N. When a large reflective force due to the estimation error is generated, as shown in circle A and B of Fig. 7(a), undesirable oscillation and motion contrary to the intentions of the human operator appear, as shown in circle A and B of Fig. 7(b). It is necessary to prevent the unexpected large reflective force that incurs the undesirable behavior and threatens the safety of the haptic system. The AOL limits the reflective force due to the estimation error and alleviates the negative effect, as shown in Fig. 8. The solid line is the output force from the controller and the line with the ‘pentagram’ is the estimated force in Fig. 8(a).

IV. CONCLUSION

The adjusting output-limiter (AOL) monitors the maximum permissible force to guarantee the passivity of the haptic system at every sampling instant. The AOL adjusts the reflective force while sacrificing the fidelity of the reflective force, only if the force computed from the
The deformation model is larger than the maximum permissible force. Otherwise, the fidelity of the reflective force is maintained and the passivity of the system guaranteed.

Only the magnitude of the reflective force is used in the proposed control method regardless of the properties of the employed reflective force models. Hence, the AOL guarantees stable haptic interaction with deformable objects, even when the impedance of the deformable objects is unknown, time-varying, and/or non-linear. In addition, the AOL alleviates the negative effects of large estimation errors. The control method presented in this paper allows the design of force-deliction models without taking into account the stability of the models. The presented AOL can be used for both the impedance and admittance-type haptic systems. It can also handle multiple degrees-of-freedom systems.

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REFERENCES


