Directionally Transparent Energy Bounding Approach for Multiple Degree-of-Freedom Haptic Interaction

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Abstract This paper presents a multiple degree-of-freedom (dof) energy bounding approach (EBA) to enhance directional transparency while guaranteeing stability for multiple-dof haptic interaction. It was observed that the passivity condition for multiple ports may lead to some oscillatory limit cycle behaviors in some coordinate directions even though the total sum of energy flow-in is positive, meaning that the system is passive. The passivity condition, therefore, needs to be applied to each coordinate in order to avoid oscillatory behavior by keeping each energy flow-in always positive. For guaranteeing passivity, which in turn, stability in each coordinates, the EBA is applied. For multiple-dof haptic interaction, however, the EBA in each coordinate may distort the direction of the force vector to be rendered since the EBA may cut down the magnitude of the force and torque vectors to be rendered in order to ensure the passivity. For avoiding this problem, a simple projection method is presented. The validity of the proposed algorithm is shown by several experiments.

Keywords **:** haptics, transparency, passivity, stability

본 연구는 2008 년 지식경제부 및 정보통신연구진흥원의 대학 IT 연구센터 육성·지원사업의 연구결과로 수행되었음 (IITA-2008-C1090-0804-0002)

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1. Introduction

There have been many efforts to construct stable haptic interaction systems. Colgate and Schenkel [1] discussed the stability issues using the passivity theorem and proposed the concept of the virtual coupling. The virtual coupling was further investigated by Colgate and Brown [2] as the coupling network that restricts the achievable impedance range of virtual environment within the range of Z-width. Hannaford and Ryu [3] and Ryu et al. [4-5] proposed the time-domain passivity control algorithm with separate passivity observer (PO) and controller (PC) which enables them to monitor energy flow and dissipate the excessive energy in real-time. Kim and Ryu [6-7] proposed the energy bounding algorithm (EBA) for a single-dof case, which restricts the excessive energy generated during haptic interaction within permitted limits to guarantee stability.

However, there were a few approaches which deal with stability and transparency issues in multiple-dof haptic interaction, although various multiple-dof haptic rendering approaches with the virtual coupling approach for stability have been introduced (e.g [8-10]) in such haptic applications as virtual prototyping, medical simulation, digital modeling, and entertainment for a higher level of realism and immersiveness of haptic interaction. Recently, Preusche et al. [11] proposed extention of the time-domain passivity control algorithm to multiple-dof haptic interaction. For keeping total sum of generated energy positive, they assigned adaptive damping along the direction of force and torque vectors that are calculated from a virtual environment. In this approach, not individual energy along force vector or along torque vector but total sum of energy of a multiport system is monitored to decide the amount of energy dissipation. Distribution of the energy dissipation to each coordinate direction may be arbitrary as long as the total sum of energy is kept positive.

It was, however, observed in multiple-dof haptic interaction examples such as sliding as well as pushing against a virtual wall with high normal stiffness that the passivity condition for satisfying positive total sum of energy in multiple ports may lead to oscillatory behavior in the coordinate direction with negative energy, even though the total energy is positive. In this case, transparency is lost along this coordinate direction even though the multiple-dof haptic interaction is passive and therefore stable. Hence, this paper argues that the passivity condition needs to be applied to each coordinate direction in order to provide directionally transparent haptic sensation to the human operator. For guaranteeing passivity in each coordinate direction, the EBA is applied. For multiple-dof haptic interaction, however, the EBA in each coordinate may distort the direction of the force vector to be rendered since the EBA may cut down the magnitude of the force and torque vectors to be rendered in order to ensure the passivity. For avoiding this problem, a simple projection method is presented. The validity of the proposed algorithm is shown by experiments. Some preliminary results on the proposed method are in [12].

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2. Oscillatory Behaviors in Passive Multiple-dof Haptic Interaction

For n-DOF haptic device, the passivity condition can be written as,

For all admissible forces f_i and velocities v_i,

$$T\sum_{k=0}^{n-1}\left\{F_1(k)v_1(k)+\ldots+F_n(k)v_n(k)\right\}\geq 0 \qquad (1)$$

Eq. (1) guarantees positive values of the total sum of energy flow-in even though some terms have negative values. This approach, however, may not provide full realism of haptic interaction. Even though the haptic system satisfies the condition in Eq. (1), the force and torque response may show an oscillatory and undesirable motion in the axis with negative energy flow-in. For example, consider an interaction with the virtual wall, which contains the x-directional friction force and y-directional normal force. Figure 1 shows the experimental condition. In this experiment, a commercial 2-DOF haptic device, the ImpulseEngine 2000 is used [12]. The virtual environment's stiffness is set up as 40kN/m and the frictional damping is 10Ns/m. The stability control algorithm EBA is set up to operate when the total sum of the energy flow-ins becomes negative.

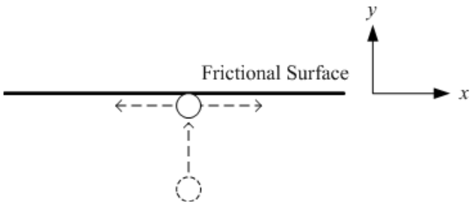


Figure 1. Virtual wall with frictional surface.

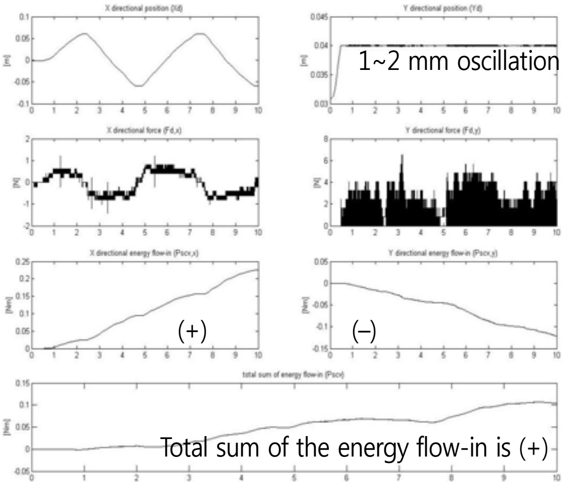


Figure 2. Experimental results with Eq. (1).

As shown in Figure 2, even though total sum of the energy flow-ins becomes positive, the y-directional interaction shows small oscillations and it gave undesired force feedback to human operator. Moreover, there was no chance to begin to operate a stability algorithm, since the total sum of the energy flow-ins were always positive. In conclusion, the passivity condition in Eq. (1) may not be feasible for very stiff contact simulation.

On that account, we describe the passivity condition for stable multi-DOF haptic display for each orthogonal coordinate axis at global reference frame as follows:

For each orthogonal coordinate axes $i=1,2,3,\ldots,n$,

$$T\sum_{k=0}^{n-1}F_i(k)v_i(k)\geq 0 \qquad (2)$$

Eq. (2) requires keeping passivity condition at each orthogonal coordinate axis, and consequently, a user can be provided stable force feedback along any axis. For instance, stability algorithm, which is based on the passivity condition in Eq. (2), shows more desirable results for the same experimental condition as shown in Figure 3. In contrast to the former results, oscillations are hardly found in y-directional interaction.

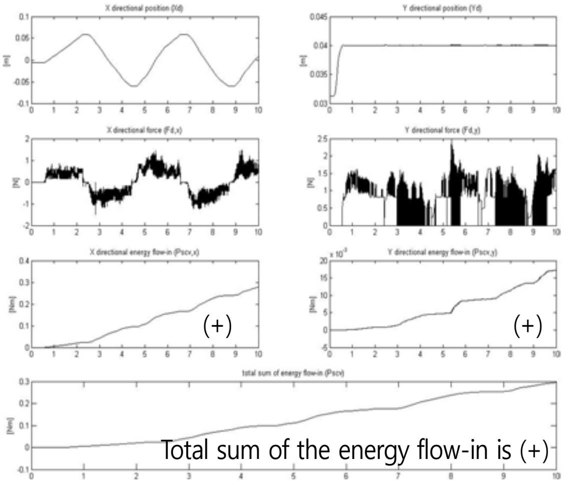


Figure 3. Experimental results with Eq. (2).

Now, it is possible to modify the control law and the bounding laws of the original EBA to be able to support multi-DOF haptic interaction. For an impedance display and for each orthogonal coordinate axis $i = x, y, z, \theta, \phi, \psi$,

Control law:

$$F_{d,i}(n) = F_{d,i}(n-1) + \beta_i(n)\Delta x_{d,i}(n)$$

where

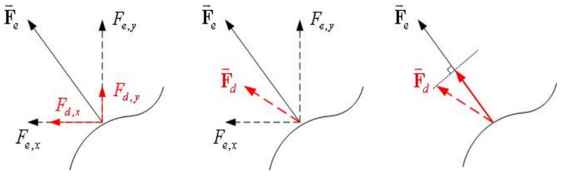
$$\beta_i(n) = \frac{F_{e,i}(n) - F_{d,i}(n-1)}{\Delta x_{d,i}(n)} \quad for\ \Delta x_{d,i}(n) \neq 0 \qquad (13)$$

Bounding laws:

$$\beta_{i,\max}(n) = \min\left(c_{1,i}, \gamma_{i,\max}(n)\right),$$
$$\beta_{i,\min}(n) = \gamma_{i,\min}(n)$$
$$\gamma_{i,\max}(n) = c_{2,i} - \left(\frac{F_{d,i}(n-1)}{\Delta x_{d,i}(n)}\right) + \sqrt{c_{2,i} + \left(\frac{F_{d,i}(n-1)}{\Delta x_{d,i}(n)}\right)^2},$$
$$\gamma_{i,\min}(n) = c_{2,i} - \left(\frac{F_{d,i}(n-1)}{\Delta x_{d,i}(n)}\right) - \sqrt{c_{2,i} + \left(\frac{F_{d,i}(n-1)}{\Delta x_{d,i}(n)}\right)^2}$$

3. Directional Transparency

By the passivity condition in Eq. (2), the proposed multiple-dof EBA can provide stability and no oscillatory behavior along any orthogonal coordinate axis. For *n*-dof haptic interaction, however, there may be another directional transparency problem, i.e., the direction of the rendered force may be distorted. For example, when interacting with a 2-dof object, as shown in Figure 4(a) and (b), the rendered force vector $\vec{F}_d$ may not be along the commanded virtual environment force vector $\vec{F}_e$ because the magnitude of rendered forces in x and y directions may be reduced separately for satisfying the passivity condition in Eq. (2) by the proposed multiple-dof EBA.



(a) (b)

(c)

Figure 4. Force direction distortion and projection.

A directionally transparent force/torque feedback is required for the human operator to feel accurate contours and surface properties of a virtual object of general shape. Therefore, distortion of the direction of the rendered force and torque vector should be avoided. Correcting the direction can easily be done by projecting the proposed multiple-dof EBA force to the direction of the commanded force as follows:

$$\vec{F}_{d,\,proj} = \vec{F}_d \cdot \frac{\vec{F}_e}{\left\|\vec{F}_e\right\|} \qquad (3)$$

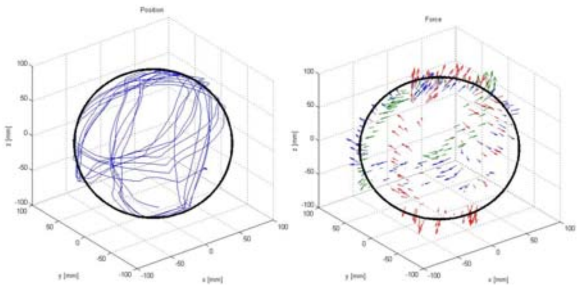


Figure 5. Experimental results of the virtual sphere *before* applying the multiple-dof EBA.

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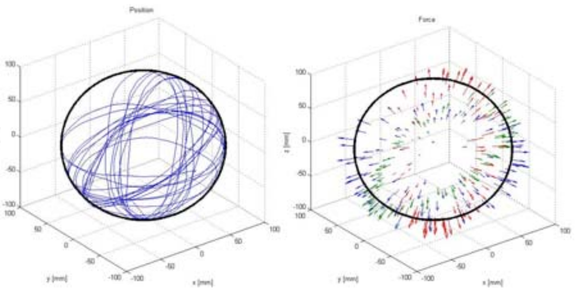

Figure 6. Experimental results of the virtual sphere *after* applying the multiple-dof EBA.

The direction and the length of arrow demonstrate the direction and the magnitude of the force vector, which is displayed to the human operator.

Figure 5 and 6 show the experimental results for a virtual sphere with a radius of 90mm. The 3-dof PHANToM [14] is used for the experiments and the device is driven at a sampling rate of 1 kHz. Both of virtual environments are set with a stiffness of 5kN/m. As seen in these figures, the proposed multiple-dof EBA can make the direction of the rendered force vector coincide with the normal direction of the virtual environment, and therefore, the human operator can easily track the surface of the virtual environment. Even though only 2-dof and 3-dof interactions are shown in this paper, the proposed multiple-dof EBA can also be applicable to more general multiple-dof cases.

4. Conclusion

A multiple-dof EBA for stable and directionally transparent multiple-dof haptic interaction control is presented. The proposed multiple-dof EBA requires that the passivity condition must be satisfied for each orthogonal coordinate axis of the fixed global reference frame in order to avoid the unwanted force feedback such as oscillation. The problem that the proposed multiple-dof EBA may distort the direction of the rendered force vector was solved by projecting the direction of the rendered force vector onto the desired force direction.

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