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Haptic Interface Protocol for FEM-based Deformable Model and Effects on Fineness of Force Feedback and Perceived Hardness

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***Abstract*— The remote haptic collaboration system between operating and assistant surgeons causes both shift and step delays of force feedback, and then makes users feel coarse reaction forces and different hardness of the object. In this study, we propose a haptic interface protocol for finite-element-method based deformable objects, in order to achieve a high update rate of force calculation. The method exports the necessary information for calculation of reaction forces from the simulation loop to the haptic loop. The experimental results indicated that the proposed method improved the fineness of force feedback and subjective hardness significantly.**

I. INTRODUCTION

THE simulation of non-rigid objects with haptic feedback is in demand, especially in medicine. For instance, surgical training requires simulating organ deformation to construct a safe and efficient training environment. The FEM-based physically deformable model is currently popular for surgical simulation [1], because the deformation is solved based on continuum mechanics, and real-time simulation is possible by applying recent methods [2], [3]. However, the computational cost remains high if external forces are applied to the boundary nodes. The high load of physics simulation causes stepwise reaction forces and makes the user feel coarse reaction forces. We call this delayed response "a step delay." In addition, the haptic system with network communication, e.g., a remote haptic collaboration system sharing a virtual environment between persons, has a shift delay as well as a step delay. In other words, data transfer via computer network causes the phase shift of the input data. As a result, the system would make a user feel the object softer or harder than it actually is.

In this study, we propose a hatpic interface protocol for non-rigid bodies to enable frequent updates of reaction forces. Previous studies have reduced the difference between two threads: the simulation thread and the haptic thread, especially for rigid objects [4], [5], while this paper focuses on non-rigid objects, such as finite element method (FEM)-based deformable objects. We focus on separating the calculation steps of the reaction forces and defining intermediate representation, which is the data exported from the simulation loop to the haptic loop. This paper describes the proposed method, evaluation of its effects on the perceived fineness and hardness of force feedback, and the prototyped haptic collaboration system.

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II. APPROACH

A. Problem

Fig.1 illustrates the produced reaction forces according to the displacement of a non-rigid object by a manipulator, i.e., a finger. Fig.1 (a) shows that the reaction forces are updated at a high update rate. Fig.1 (b) shows that the reaction forces are updated at a low rate due to the high load of physical simulation. Here, finger positions are NOT used to calculate reaction forces partly. This step delay makes the user feel coarse reaction forces. Though the discrimination cues of an object's compliance are still controversial [7], [8], it has been reported that the terminal-force cue is significant in softness discrimination [7]. From this point of view, in the case of shift delay as shown in Fig.1(c),(d), the force when the displacement was at a maximum becomes smaller than the maximum force in a stroke, so that the user feels the object as softer than it is. This does not mean that the perceived hardness depends only on the force feedback. We intended to observe the change in the perceived hardness by the step and shift delays and to examine the effects of the proposed method on the change. As the proposed method reduces the step delay in theory, the system would improve perceived hardness.

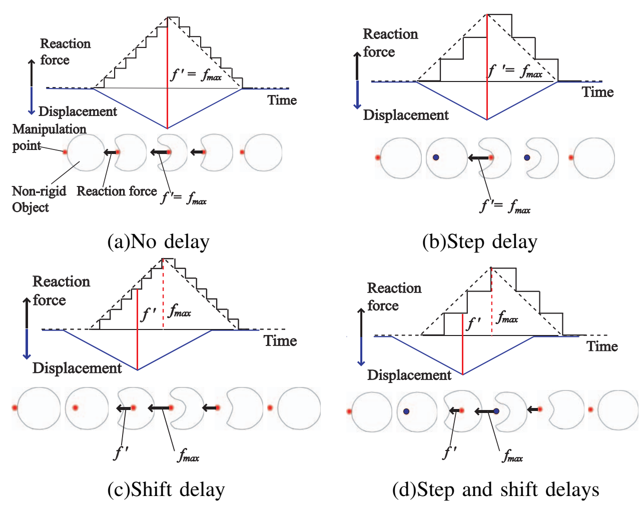


Fig. 1. The produced reaction forces according to the displacement of a non-rigid object by the manipulator. (a) If there was no delay, the forces were updated at a high rate. (b) If there was a step delay, the forces were updated at a low rate. (c) If there was a shift delay, the terminal-force f' was smaller than the maximum force in a stroke f_{max}. (d) In the event of both step and shift delays the terminal-force f' is further smaller than the maximum force in a stroke f_{max}.

B. Object deformation and contact forces

Recent advances in information technology have enabled the real-time high-fidelity simulation of an object's deformation based on continuum mechanics. FEM is one of the most popular solutions for solving differential equations that represent the relationship between the force and displacement of a compliant object. The fundamental equation is the stiffness equation $\mathbf{f} = \mathbf{K}\mathbf{u}$, where $\mathbf{f}$ and $\mathbf{u}$ are the vectors of nodal force and displacement, respectively, and $\mathbf{K}$ is the stiffness matrix. Although the computational cost is quite high, the computational cost in real-time processing can be reduced drastically by pre-processing. A numerical solution must be finished for less than 1ms for fine force feedback of more than 1kHz. The displacement is calculated using the inverse of the stiffness matrix $\mathbf{L} = \mathbf{K}^{-1}$ as shown in Eq.1. The nodes are categorized into the following three types: (i) contact nodes by a user, (ii) colliding boundary nodes, to which external forces are applied, and (iii) all other nodes. The stiffness equation is shown in Eq.2. The forces of the contact nodes are calculated as shown in Eq.3, given that external forces of other nodes are zero.

$$\mathbf{u} = \mathbf{L}\mathbf{f} \tag{1}$$

$$\begin{pmatrix} \mathbf{u}_c \\ \mathbf{u}_b \\ \mathbf{u}_o \end{pmatrix} = \begin{pmatrix} \mathbf{L}_{cc} & \mathbf{L}_{cb} & \mathbf{L}_{co} \\ \mathbf{L}_{bc} & \mathbf{L}_{bb} & \mathbf{L}_{bo} \\ \mathbf{L}_{oc} & \mathbf{L}_{ob} & \mathbf{L}_{oo} \end{pmatrix} \begin{pmatrix} \mathbf{f}_c \\ \mathbf{f}_b \\ \mathbf{f}_o \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} \mathbf{f}_c \\ \mathbf{f}_b \end{pmatrix} = \begin{pmatrix} \mathbf{L}_{cc} & \mathbf{L}_{cb} \\ \mathbf{L}_{bc} & \mathbf{L}_{bb} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{u}_c \\ \mathbf{u}_b \end{pmatrix} \tag{3}$$

$$= \begin{pmatrix} \mathbf{M}_{cc} & \mathbf{M}_{cb} \\ \mathbf{M}_{bc} & \mathbf{M}_{bb} \end{pmatrix} \begin{pmatrix} \mathbf{u}_c \\ \mathbf{u}_b \end{pmatrix} \tag{4}$$

where subscripts c, b, and o represent contact nodes by a user, colliding boundary nodes, and the other nodes, respectively, and the matrix $\mathbf{M}$ is the inverse matrix of a part of $\mathbf{L}$. The computational cost in real-time processing increases exponentially as the number of colliding boundary nodes increases because the size of the matrix in Eq.3 increases. The displacement of the contact nodes is the foot of the perpendicular of the manipulator positions on the polygon.

The contact force $\mathbf{F}$ at a point on the contact polygon is calculated from the nodal forces of the contact nodes [3].

$$\mathbf{F} = \sum_i w_i \mathbf{f}_i \tag{5}$$

where $\mathbf{f}_i$ is the nodal force of the node i on the contact polygon, and w_i is its area coordinates, whose total is one. The reaction force has the same magnitude and the opposite direction of the contact force.

C. Intermediate representation for the FEM-based deformable model

The computational cost for calculation of the inverse matrix is high, while the multiplication of the matrix and the displacement vector is relatively costless. Therefore, we divide the procedure of calculating the reaction force into two parts: (i) calculation of the inverse matrix $\mathbf{M}$ and (ii) calculation of contact force $\mathbf{F}$, which includes multiplication of the inverse matrix and the displacement vector and interpolation of the nodal forces on a contact polygon. The first part is computed in the simulation loop, while the second part is computed in the haptic loop. Eq.4 gives the equation:

$$\mathbf{f}_c = \tilde{\mathbf{M}} \begin{pmatrix} \mathbf{u}_c \\ \mathbf{u}_b \end{pmatrix} \tag{6}$$

where $\tilde{\mathbf{M}} = \begin{pmatrix} \mathbf{M}_{cc} & \mathbf{M}_{cb} \end{pmatrix}$. The local geometry and the matrix $\tilde{\mathbf{M}}$ are transferred from the simulation loop to the haptic loop. Fig.2 shows the procedure of the proposed method and the difference between the conventional and proposed methods. Here, we assume that the conventional method calculates reaction force in the simulation loop [3]. The manipulator positions of the haptic interfaces are updated at a high update rate. The manipulator position in the remote host is transfered via computer network with a shift delay, but at a high update rate. The manipulator positions of the hosts are buffered in the main memory, and are synchronized. As a result, the intermediate representation for FEM object enables the calculation of reaction forces at a high update rate. It must be noted that, assuming linear elasticity and one point collision without a remote host, forces can be inter/extrapolated with the displacements.

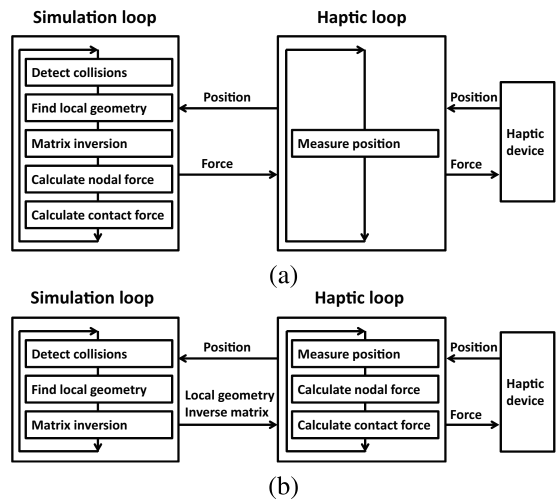
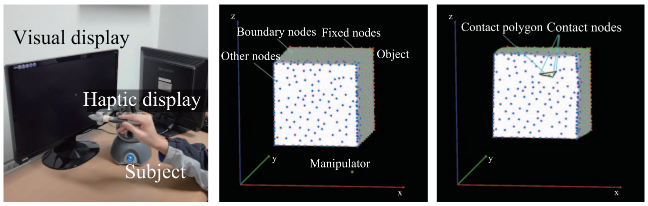


Fig. 2. Procedures of (a) the conventional and (b) the proposed methods.

III. EXPERIMENTS

A. Experimental setup and conditions

The method was implemented into the system that has an Intel Core2 Quad 2.4GHz processor, 2.0 GB of main memory, a SensAble PHANToM Omni haptic interface, and an Intel MKL numerical library. Subjective evaluation of the fineness of reaction forces and the perceived hardness was carried out. Ten subjects aged 22 to 25 participated in the experiments. The subjects manipulated a haptic interface with their right hand, even if their dominant hand was their left. Fig.3 shows an overview of the experiment and the cubic elastic object, which was chosen for the experiments to make the manipulation simple and consistent among subjects. The object had a $130 \times 130 \times 130mm$ volume, 8324 tetrahedron, and 1812 nodes. 1.0MPa Young modulus and 0.4 Poisson's ratio were set as the elastic parameters of soft tissue [1]. The rear part of the object was fixed in the space. No friction between the manipulator and the object was simulated.



(a) (b) (c)

Fig. 3. The object used in the experiments. (a) Overview of the experimental scene. (b) The object is in the initial state. (c) The object is deformed.

The subjects were asked to push the front side of the cubic elastic object with the haptic interface in two different conditions successively and to answer the difference of the perceived sensation between the two conditions. The subjects were asked to fix their arm on the desk. Before the experiments, the subjects were allowed to practice the pushing manipulation for a few minutes. The object was displayed visually in the practice period, but the object was not displayed in the experiments. Each pair of conditions was rated with a five grade scale from +2 to -2 using Scheffe's method of paired comparisons (Nakaya's modification) [6]. The subject was allowed to conduct repetitive judgment while judging all the pairs. The system controlled the following parameters:

- shift delay;
- step delay;
- haptic interface protocol.

The shift delay (S) assumed that the haptic response from the system to the user was delayed due to the network transfer. We prepared three conditions of shift delay: 0 ms, 30 ms, and 100 ms by running a loop and measuring the time. In the experiment, we called these conditions, S0, S30, and S100, respectively.

For the step delay (T) it was assumed that the haptic response from the system to the user would not be updated for a while due to the physical simulation. The step delay was implemented by increasing the number of the colliding boundary nodes. We prepared three conditions of step delay: 0 node, 150 nodes, and 300 nodes. In the experiment, we called these conditions, T0, T150, and T300, respectively.

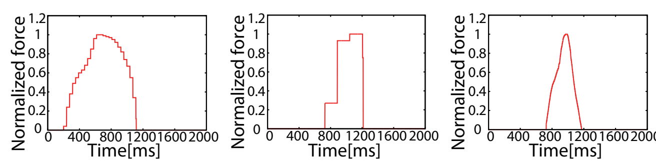
The conditions of the haptic interface protocol (P) decided whether or not the proposed haptic interface protocol was applied. We prepared two conditions. The first condition was the case of a conventional protocol with no intermediate representation. The other was the case of the proposed protocol. In the experiment, we called these conditions P0 and P1, respectively.

The aims of the three experiments were as follows:

- *Effects of step delay on fineness of reaction forces.* The aim of the first experiment was to examine the effects of the step delay on the fineness of the reaction force. The conditions were the combination of {S0}, {T0, T150, T300}, and {P0, P1}, namely six conditions, 15 comparisons in total.
- *Effects of the combination of shift and step delays on perceived hardness without the proposed method.* The aim of the second experiment was to examine the effects of the combination of the shift and step delays on the perceived hardness of an object. In this experiment, the proposed method was not applied due to the large number of combinations. The conditions were the combination of {S0, S30, S100}, {T0, T150}, and {P0}, namely six conditions, 15 comparisons in total.
- *Effectiveness of the proposed method on perceived hardness.* The aim of the final experiment was to verify the effectiveness of the proposed method to improve perceived hardness, even in the case of the combination of stepwise and shifted forces. The conditions were the combination of {S0, S30}, {T0, T150}, and {P0, P1}, namely eight conditions, 28 comparisons in total.

B. Results and discussions

The reaction forces were recorded when a user pushed the object. Fig.4 shows the reaction forces with and without the proposed method in the conditions of step delay, T150 and T300. In the graph, the reaction forces were normalized by the maximum force in the stroke. The reaction forces without the proposed method were updated at a lower rate and became stepwise. However, the reaction forces with the proposed method were updated at a higher rate and were changed smoothly.



(a) (b) (c)

Fig. 4. Reaction forces with and without the proposed methods: (a) step delay T150 without the proposed method; (b) step delay T300 without the proposed method; and (c) step delay T300 with the proposed method.

For the first experiment, the rating of the subjective fineness is shown in Fig.5. The main effect of fineness was significant; ($p < 0.05$). First, a decrease in fineness was found to correlate with an increase in the step delays. In the case of the conventional protocol (P0), the fineness between the conditions T0 and T150, T0 and T300, and T150 and T300 were significantly different. A significant difference was found between the conventional and proposed methods in the case of the step delay with T150 and T300. The results of the first experiment indicated that the fineness is decreased by the step delay, while the degraded fineness is improved by the proposed protocol.

For the second experiment, the rating of the subjective hardness obtained is shown in Fig.6. The conditions are the

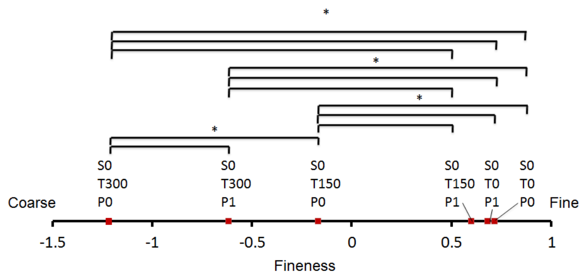


Fig. 5. The results of the first experiment: the subjective fineness.

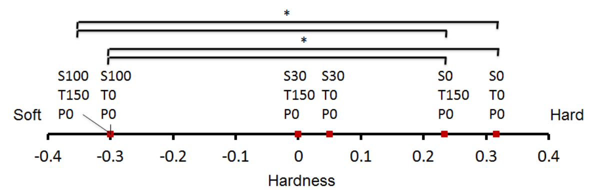


Fig. 6. The results of the second experiment: the subjective hardness.

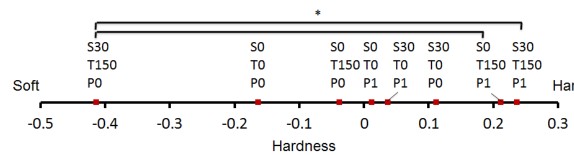


Fig. 7. The results of the third experiment: the subjective hardness.

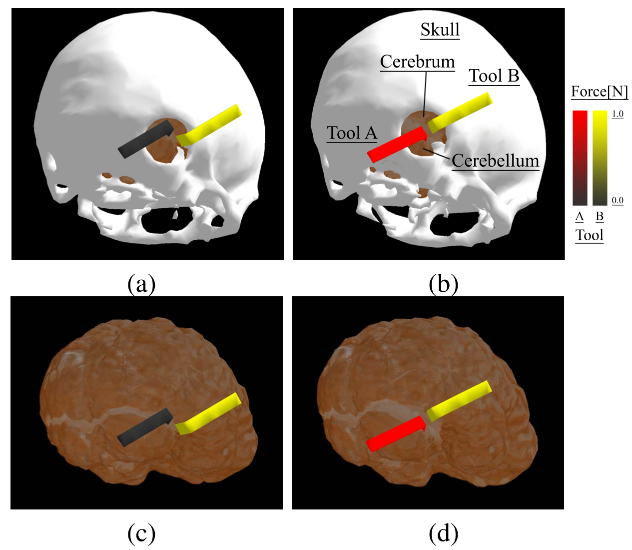


Fig. 8. The remote haptic collaboration system. (Upper) Skull is displayed.

combination of {S0, S30, S100}, {T0, T150}, and {P0}. The main effect of hardness was significant; ($p < 0.05$). Regardless of the conditions of step delay, a significant difference was found between the shift delay S0 and S100. The results of the second experiment indicated that the perceived hardness in the case of shift delay S100 was significantly lower than in the case of no shift delay.

For the third experiment, the rating of the subjective hardness is shown in Fig.7. The main effect of hardness was significant; ($p < 0.05$). In the condition of the combination of shift and step delays (S30-T150), the perceived hardness with the proposed method (P1) was significantly higher than without the proposed method (P0). The results indicated that the proposed method with a step delay made a user feel a higher hardness compared with no proposed method.

From the results of the experiments, we summarize the following findings: (A) the proposed method is effective at improving the fineness of force feedback, which is caused by a step delay due to the high load of physical simulation, and (B) the proposed method is effective at reducing the decrease in perceived hardness that is caused by shift delay. It must be noted that the examined conditions of the experiments in this paper were limited because the paired comparisons required of subjects an enormous amount of time and effort in trying all combinations among the conditions. However, the experiments were proper for examining the existence of the influence of step and shift delays on the fineness of force feedback and subjective hardness, and for examining the effectiveness of the proposed method on the influence of step and shift delays.

Finally, the haptic collaboration system for neurosurgery was prototyped as shown in Fig. 8. Two connected hosts transfer manipulating tool positions of the users via Ethernet mutually. One novice tried excluding cerebellum downward by tool A, and the other novice tried excluding cerebrum upward by tool B, in a coordinated manner. The manipulation of one person influenced on the reaction forces of the other person, mutually. A 3D texture of the brain substances, which were deformed in the simulation, were obtained by MRI.

IV. CONCLUSION

In this paper, we proposed a haptic interface protocol for the FEM-based deformable model to achieve fine and accurate force feedback in remote haptic collaboration systems. The method divided the procedure of calculating reaction forces into two steps. The results of the experiment showed that the fineness of force feedback and the perceived hardness was improved by using the proposed method.

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