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Cooperative Object Manipulation in Virtual Space using Virtual Physics

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Abstract:

This study focuses on precise and natural cooperative object manipulation by multi-users in a virtual space. We first considered the advantages of direct virtual object manipulation by multi-users' hands and the necessity of mechanical restriction between them. Here, we applied an illusion between the visual and haptic sensations to create realistic cooperative manipulation when using VR devices that cannot simulate entire physics. We introduce two virtually-expanded physical laws: “virtual mechanical equilibrium on a rigid object” and “exclusive object arrangement”. We have built a trial system with two hands according to our proposed design, and the experimental results demonstrate the effectiveness of our proposed method for both-hands manipulation. This method's aim is to allow users to exchange intentions of manipulation through haptic and visual channels by using limited VR devices.

Introduction

3-D CAD systems in virtual space is one of the anticipated applications of VR technology. Special features of VR include 'Real-time', '3-D' and 'Direct manipulation'. One can suppose that the next-generation design processes will be significantly affected by these VR technology.

In the first step of design, a user can draw each unit part in a 3-D virtual space. S/he can use not only conventional 3-D drawing instruments but also highly intuitive methods such as gestures or voice control in this step. After the designer makes unit parts, their realistic textures make it possible to join them together as if they were real parts. Furthermore the designer can directly confirm usability of target objects handling the virtual assemblies. If mismatch is found in any part, it is easy to restart from the primary drawing step and retouch the parts. Within the whole process, the designer can receive the support of tele-connected collaborators or agents in the virtual space.

Even though many studies have been done in this field, it is difficult to construct such an ultimate multipurpose virtual environment. We also have been investigating next-generation VR and its applications. As one solution, we have introduced methods that provide a user with a substantially realistic feeling of manipulation without simulating the entire physics.

In this paper, we focus on cooperative object manipulation with multi-hands, either both-hands of one user or a number of users’ hands, in a virtual space. We first consider the features of manipulation with multi-hands in real space. When one real object is held by multi-users, each user's motion is transmitted to the collaborator through the object. To realize the same natural operation in a virtual space, the virtual space has to somehow simulate this mechanical restriction between the hands.

Accordingly, we applied an illusion between the visual and haptic sensations to create realistic cooperative manipulation with VR devices that cannot simulate entire physics. To generate the illusion, our method is based on two virtually-expanded physical laws. This method generates realistic feeling without simulating dynamics perfectly. We have designed a trial system that adopts these methods, and the experimental results of using the system show the effectiveness of the proposed method. In the conclusion, we introduce future works that apply this basic manipulation method.

Cooperative object manipulation

In this section we consider the advantages of multi-hand manipulation in daily life.

Issues in multi-hand manipulation in real space

When we hold a large or heavy object, we use both-hands. We also use them to manipulate the object accurately and carefully. As farmer features, a virtual desk can weight 0 kgf in virtual space freeing the user from such fatiguing tasks, then we don't have to join together for this purpose. As the latter features, we can suppose that they are also useful in virtual space. First, we group these advantages into one user’s both-hands manipulation.

• Precise manipulation

When a user holds one end of a bar by one hand, the pointing accuracy of the other end decreases in proportion to the distance from the held end. In the case of both-hands manipulation, we use both-hands

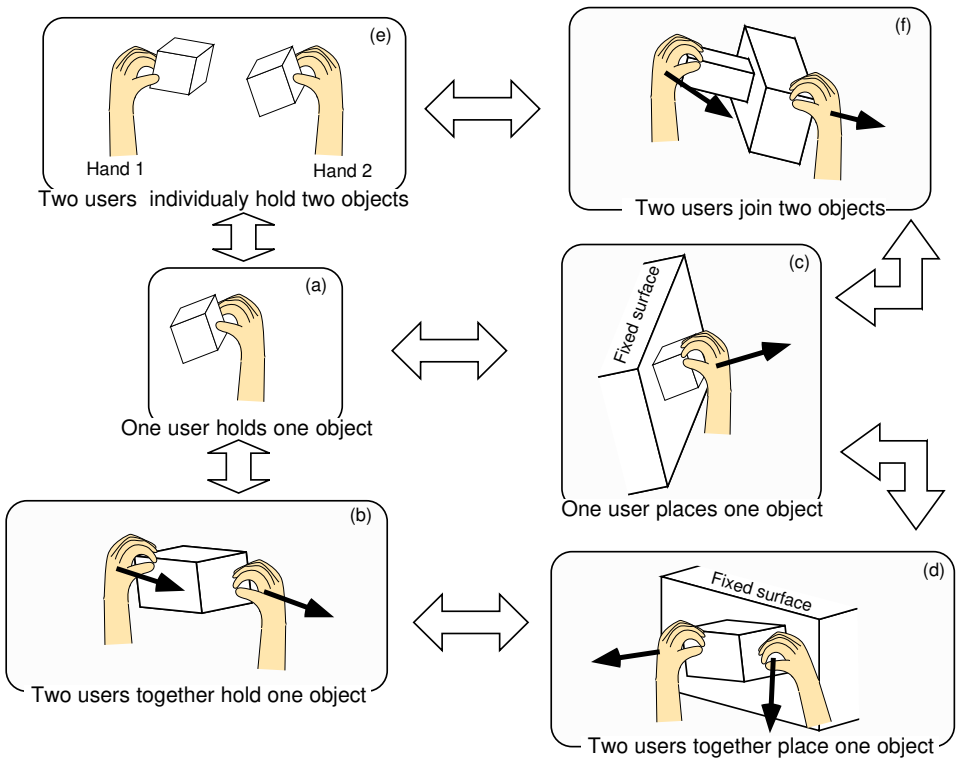


Figure 1 Transition diagrams of object manipulation with two hands

as a pivot and the affected point. Moreover we dynamically change the roles of them for effective operation. Applying a dominant arm rule or a preferential right rule, this strategy was introduced in virtual object manipulation with both-hands in a virtual space (Zeleznik 1997, Mlyniec 1996).

• Redundancy in DOF (degree of freedom)

To handle an object in 3-D space, at least a 6 DOF manipulator is necessary. However, when we use one 6 DOF manipulator, the status of all joints is fixed uniquely with the object's motion. Moreover, when the DOF of the manipulator is reduced around singular points, it is hard to freely handle. By holding one object with some 6 DOF manipulators, the DOF acquires redundancy, thus improve the effectiveness of manipulation.

• Effectiveness

The results from ergonomic studies show that manipulation with both-hands is more effective than with one hand. Buxton (1986) showed that task completion time with both mouse and slider was shorter than the time with only one mouse for manipulation. Wiesendanger (1993) reported that temporal coordination is related to the effectiveness of both-hands actions. These results indicate that a type of relationship between both-hands should be displayed to the user to improve the effectiveness of multi-hand manipulation.

Manipulation with two hands

Next, we consider typical object manipulation phases using two hands in daily life. As mentioned above, we often use both-hands when we move an object or put different objects together precisely. Fig. 1 shows transition diagrams of typical object manipulations using two hands in real space.

First, when a hand grasps an object that has been handled by another hand, from phase (a) to (b), the positional relationship between the hands is fixed and the object's motion depends on them. One hand's motion is transmitted to the other hand through the object.

When a user places the handled object on a fixed surface, from phase (a) to (c), parts of the object's DOF and the hand's DOF are constrained on the fixed surface. At that time, the user receives reaction force from the surface.

When two hands hold one object and together place it on a fixed surface, from phase (b) to (d), parts of the object DOF and the hands' DOF are constrained on the fixed surface. Additionally, each hand's positional relationship is fixed and it receives reaction force from the fixed surface and the other hand.

Finally, when two hands combine two objects with each other, from phase (e) to (f), a part of each object's DOF is relatively restricted, and its overall DOF depends on the two hands' positions. One hand's motion and applied force are simultaneously transmitted to the other hand through the constrained face.

In the shaded phases of the diagram, the hand's motion is restricted by the other hand or the fixed surface. Additionally, overlapping between objects and the fixed surface is avoided. Therefore, if these features can somehow be realized in virtual space, the user should be able to precisely handle virtual objects with a successful feeling of manipulation.

Most handling operations for complex objects can be reduced to combinations of these basic manipulations. Moreover, these phases can be easily expanded to multi -hand manipulation.

Mechanical restriction of cooperative handling

In the real world, when an object is handled with only one hand, the number of DOF of the hand is the same as that of the object. When **n** hands are handling one object together, the numbers of DOF of the

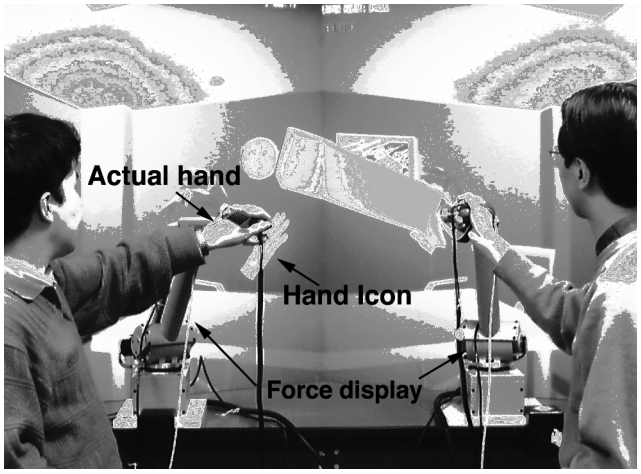


Figure 2: Trial system for cooperative manipulation

inputting hands are 6**n**. If the object is rigid, mechanical restriction fixes positional relationships among the grasping hands, and the motion of the object is determined uniquely from them. When a user pushes the object, this action is transmitted to the other user through the object. In other word, they can handle it together by sharing haptic sensations.

In the simplest VR system using only a glove-like device and a magnetic positional sensor, the user receives only visual feedback from a visual display (Barrus 1996, Carlsson 1993, Noma 1995, Palm 1996, Singh 1994). Of course, such a system cannot physically restrict the user's motion , so many of them disable the function of handling one object by multi-users.

Mechanical limitation using force display

In our proposal, we introduce a force display to physically restrict the users' motion. The force display generally resembles a mechanical robot arm and can generate reaction force to the user.

Many haptic feedback systems have been studied. (Brooks 1990, Howe 1992, Hayward 1994, Fasse 1994, Massie 1994) The results of these studies showed that an ideal force display for simulating realistic haptic sensation requires a robot arm with the following features.

The ideal force display must:

- Suppress the human muscles sufficiently
- Follows the user's entire motion
- Never injures a user

Since these features are conflicting, it is difficult to realize such an ideal force display . Fig. 2 shows our trial system described later. Two custom-made force displays are used in this system. Each of them has three actuated joints to generate a maximum of 10N reaction force at a grip on the end. It is, however, insufficient to apply a perfectly rigid mechanical restriction to the user's hand.

Proposed methods for cooperative object manipulation in virtual space

As a solution, we focused on the human illusion between visual sensations and haptic sensations. If visual information is inconsistent with haptic information, users are more influenced by visual sensation than haptic sensation. Some studies applied this illusion to a one hand VR system (Hogan 1990, Noma 1996, Sriniversan 1996).

In simulating the exact mechanical restriction with the limited VR devices, we introduced method based on two virtually-expanded physical laws: 'virtual mechanical equilibrium on a rigid object' and 'exclusive object arrangement'. The former method allows users to handle one object together, and the latter method realizes precise manipulation. These methods present visual and haptic information that is retouched as a situation of manipulation, and their combination gives the illusion of feeling cooperative manipulation.

Virtual mechanical equilibrium on a rigid object

When multi-users together handle a rigid object in real space, the positional relationship between the grasping points are fixed. Each user receives reaction force that is in the opposite direction and equal to the acting force. The motion of the object is determined by the equilibrium of the acted forces by the users.

In Fig. 3-a, the user-**n** grasps the object at $\dot{X}_n$ in a virtual space. A point $\dot{C}$ and the axis of coordinates $\dot{B}$ is fixed on the object to represent the object's motion. In the real space, the actual hand's point $\dot{P}_n$ that follows user-**n**'s hand position is equal to $\dot{X}_n$. Consequently, $\dot{C}$ and $\dot{B}$ are determined from all hand positions.

In perfect simulating same physics in a virtual space, an ideal virtual spring should connect point $\dot{P}_n$ and $\dot{X}_n$ through universal joints (Fig. 3-b). The stiffness of all springs should be sufficient to exactly support the users' hand without causing delay. However, as previously mentioned, an insufficient force display cannot fix their positional relationships exactly.

The proposed method supplies the positional relationship only visually in the virtual space. Therefore, the actual hand-**n**'s position $\dot{P}_n$ deviates from $\dot{X}_n$, and the icon of the its hand in virtual space is drawn at $\dot{X}_n$. At that point, each user-**n** receives the reaction force $\dot{F}_n$, which is determined by the following spring models (Eq.1).

$$\vec{F}_n = k_n(\vec{P}_n - \vec{X}_n) - D_n\dot{\vec{X}}_n \tag{1}$$

where, k_n is spring factor and D_n is dumping factor of spring **n**.

The hand icon's position from visual information is inconsistent with the actual hand's position from haptic information; however, we assume that users are so much more influenced by the visual sensation than by the haptic sensation that they feel as if their hands are restricted within an exact positional error.

It is necessary to determine the object's motion from all users' actual hand positions. Our method solves physical equilibriums by using approximation. Applied force and Moment on the object $\dot{F}$ and $\dot{M}$ are defined as follows.

$$\vec{F} = \sum_{i=1}^{n} \vec{F}_i \tag{2}$$

$$\vec{M} = \sum_{i=1}^{n} \vec{M}_i = \sum_{i=1}^{n} (\vec{P}_i - \vec{C}) \times \vec{F}_i \tag{3}$$

To get the object's motions $\dot{C}$ and $\dot{B}$ in every simulation step, we use the following approximations.

$$\vec{C}(t) = \vec{C}(t-1) + u\vec{F} - s\dot{\vec{C}}(t-1) \tag{4}$$

$$\dot{B}(t) = Rot(\dot{W}, -q|\dot{W}|) \cdot Rot(\dot{M}, p|\dot{M}|) \cdot \dot{B}(t-1) \tag{5}$$

where t means approximation step, $Rot(\dot{A}, b)$ is a rotational matrix that rotates the following vector at b degrees around $\dot{A}$, and u,s,p and q are constant values. $\dot{C}(t-1)$ and $\dot{W}$ are defined as follows.

$$\dot{\vec{C}}(t-1) = \vec{C}(t-1) - \vec{C}(t-2) \tag{6}$$

$$\vec{B}(t-1) = Rot(\vec{W}, |\vec{W}|) \cdot \vec{B}(t-2) \qquad (7)$$

The physical equilibrium is filled when $|\vec{F}|$ and $|\vec{M}|$ are equal to 0. Accordingly, the approximation is stopped when $|\vec{F}|$, $|\vec{M}|$ become smaller than predefined values. Using the object's motion from the physical equilibrium, the system presents visual and haptic information on the visual display and the force display, respectively.

When n=2, as shown in the Fig. 4, this method cannot determine the rotation around a axis X_1X_2 uniquely. So the method determines this motion as defined from Eq. 8.

$$\theta = \frac{\theta_1 + \theta_2}{2} \qquad (8)$$

where θ_i is angler difference between initial posture and recent posture of hand i on the axis X_1X_2.

Exclusive object arrangement (Noma 1996)

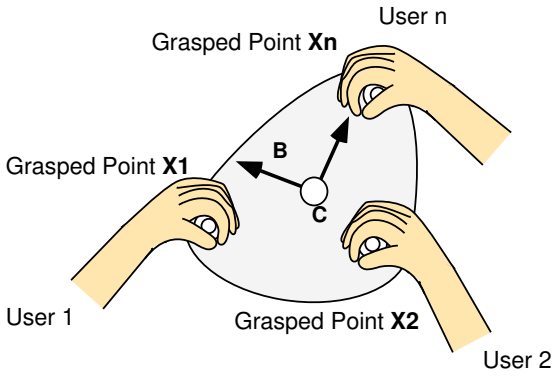
When placing a cup on a table in real space, the cup being handled never overlaps the table. The user receives a suitable reaction force caused by the collision of the cup and the table, so s/he can place it on the table precisely without making any special effort.

To realize such exclusive object arrangement in virtual space, a VR system has to detect the complex collisions of the objects and provide 6 DOF reaction force in real-time. As mentioned before, this requires time-consuming calculation and an ideal force displays.

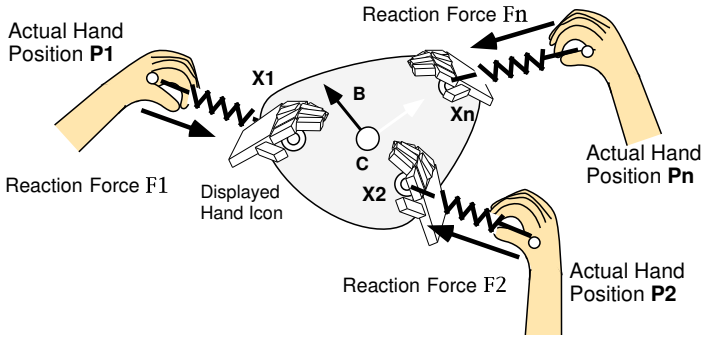
To support such a natural placement task in virtual space with limited devices, we have adopted constraints based on visual and haptic feedback among object manipulations. The concept of this approach is shown in Fig. 5.

This method visually restricts the object's motion and the hand icon in virtual space but does not restrict the user's hand motion rigidly in real space. The original DOF of the virtual object is 6, so in this method the DOF is automatically restricted to 3 to avoid overlap when the object is placed on another surface. While the handled object is restricted on the other surface, the reaction force attracts the user's hand to the constrained surface. In short, the user's hand is kept around the surface without the user being aware of motion control. If the user wants to lift the cup from the table, s/he has to intentionally pull it with a force greater than the predefined threshold against the reaction force from the table. The status of constraint is controlled by the system semiautomatically. When the user approaches the cup on the table, the system estimates the best pair of surfaces for each one and constrains them.

Therefore, these two types of feedback-based methods provide the user with highly direct manipulation, and consequently s/he can



(a) Grasping one object with three hands



(b) Manipulating one object with three hands

Figure 3: Virtual mechanical equilibrium on a rigid object

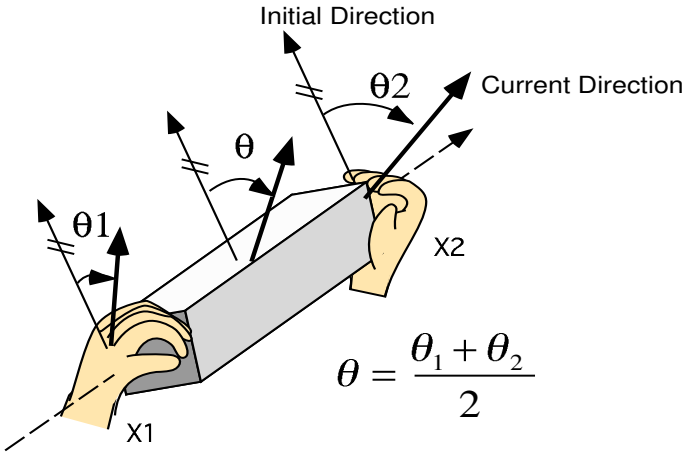


Figure 4: Rotational manipulation with two hands

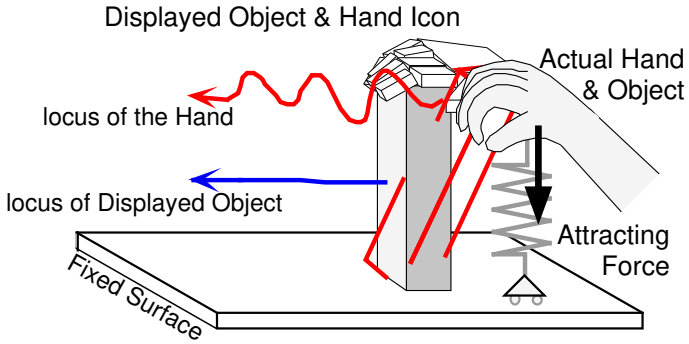


Figure 5 Exclusive object arrangement with visual and haptic methods

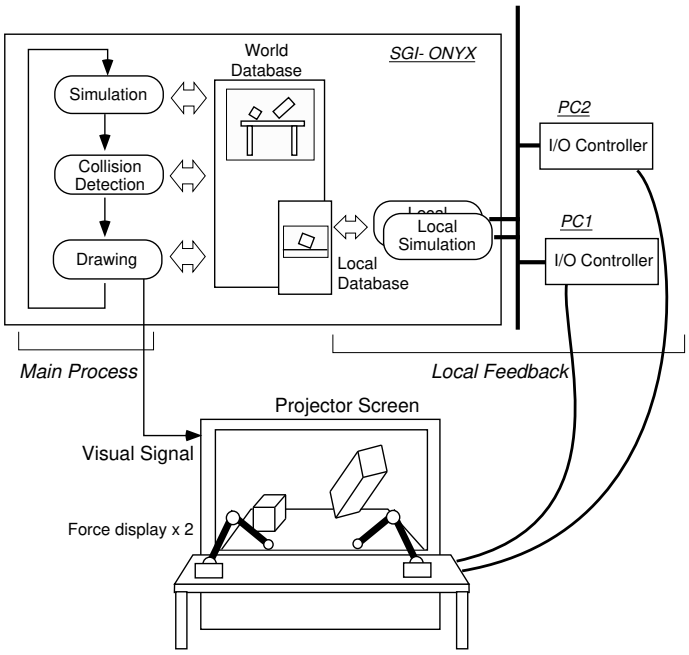


Figure 6: Block diagram of the trial system

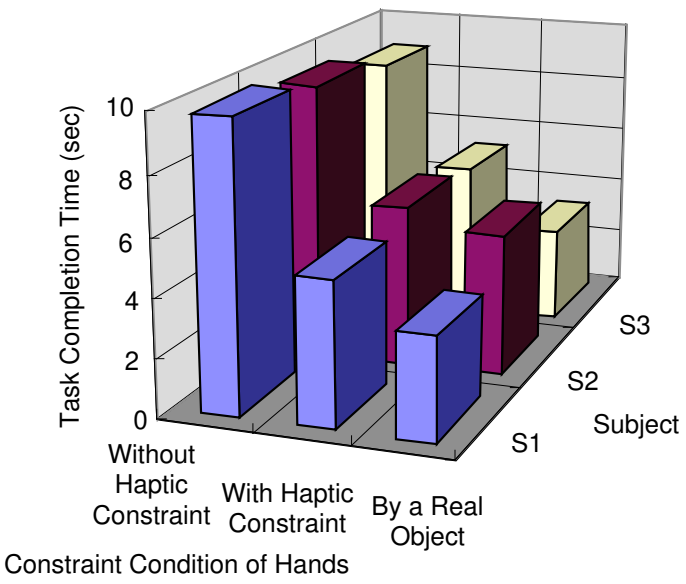


Figure 8: Task completion time of the balance game

concentrate on simply manipulating the unrestricted DOF of the cup as s/he pleases.

Manipulation with two hands in a vital world

As mentioned above, most those typical object handling operations using two hands in real space can be reduced to the manipulations shown in Fig.1. Our methods provide virtual mechanical restriction among users and virtual objects when the operational phase is in the shaded areas in Fig.1. Therefore, it is expected that users can precisely handle virtual objects together with realistic sensations in virtual space.

Trial system

Fig. 6 shows a block diagram of the trial system. All input and output devices and sensors were controlled by a SGI ONYX™ and PCs (P5, 75MHz). Two 70-inch screen projectors were used to present stereoscopic images of virtual space. The system is equipped with two force displays so that two users' hands or both-hands of one user can handle objects with the feeling of cooperative manipulation through the visual and force display. When the user wants to grasp a virtual object, s/he puts in the hand-shaped icons onto the object and clicks button at the grip of the force display.

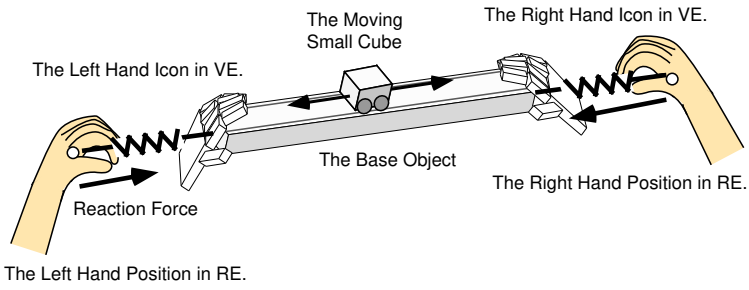


Figure 7: Experimental setup of balance game

We divided the trial system into time-consuming heavy processes and high-speed light processes. The former is named "main process" and consists of a virtual world simulating process that manages all objects, a real-time collision detecting process, and a CG drawing process. Each subprocess places such a heavy load on the CPU that they were carried out at an average of 30 Hz, depending on the number of objects and number of their polygons. The numerical database of all virtual objects is maintained by the main process, and the part of it is shared among the high-speed light processes.

These light processes are named "local feedback" subsystems. These subsystems were carried out higher than the main process nonsynchronously. They were used to reference the phase of manipulation and the actual position of the users' hands in real space and to maintains the local database of the objects around the users' hand icons. Using these data, they realize force feedback at a high enough rate. The ONYX™ and PCs were connected by ethernet. In the trial system, they were carried out at about 300 Hz.

Experiment

Configuration of experiment

A simple experiment was conducted to examine the effectiveness of a both-hands position control task with the proposed method. Fig. 7 shows the experimental configuration. Three subjects were asked to stop a small cube at the center of a base object. Each subject could move the small cube by tilting the base object with two-hands. The small cube moved on the base object freely, simulating gravity, inertia and friction. This simulation was carried out at almost 500 Hz.

For comparison, the following three modes of manipulation were used. In the mode of "Without haptic constraint", the motion of the base object is constrained only visually, in the same way as a typical VR system. In the mode of "With haptic constraint", the proposed method was used. In the mode "By a real object", the subjects held an actual wooden bar in a real environment and the motion of the bar was reflected

in the motion of the base object in the virtual environment; therefore, the positional relationship between the both-hands was fixed rigidly in the same way as real manipulation in this mode.

In each of these modes, each subject did ten trials, and we measured task completion time. When the small cube appeared at the end of the base object, a real time computer clock was started. When the small cube was near the center of the base object, the clock was stopped and the time was recorded.

Results

Fig. 8 shows the average task completion time against manipulation mode for each subject. When using the proposed method and "With haptic constraint" mode, the time required for task completion was half that of the "Without haptic constraint" mode ($P(t>7.76) = 0.01$). However, the proposed method required a little more time in the "By a real object" mode ($P(t > 3.61)=0.01$) . This indicates that even if the proposed method simulates a part of the real physics, it could improve the effectiveness of both-hands manipulation to nearly equal that of the real situation.

Discussion

In this study, we focused on precise and natural cooperative manipulation in virtual space. Our system introduced two virtually-expanded physical laws that give the users a feeling of manipulating a rigid object in virtual space with visual and haptic sensations. Although our current method is not to simulate real manipulation by using VR, we expect this method to achieve realistic cooperative manipulation. For the present, we have confirmed that the proposed method can improve effectiveness of multi-hand manipulation.

The proposed method provides only basic framework for cooperative object manipulation. In the future study, we can apply this method to any field that needs to utilize direct manipulation by multi-users.

For example, we have just started a project to build a handler for a computer aided thinking system. The system constructs human thinking with a network model. Points of the network represent each term of thinking and nodes represent similarity (Sumi 1996). The points are defined as mass and the nodes are defined as spring, so it is expected that direct manipulation with both-hands is effective for rearranging the complex thinking model to increase understanding the structure.

Additionally, we will develop a virtual elasticity display with a limited VR display. In the proposed method, handled objects are never deformed. Consequently, the next system will introduce the factor of elasticity into objects and provide the feeling of manipulating of elastic objects by using retouched visual and haptic sensations.

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