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HAPTIC AND VISUAL FEEDBACK FOR MANIPULATION AID IN A VIRTUAL ENVIRONMENT

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ABSTRACT:

This paper proposes a new method of object manipulation in a Virtual Environment that uses a visual and haptic feedback based manipulation aid. If the displayed position of the object is constrained on a face of another object in the virtual environment, a user can place the virtual object at a precise position as easily as in a real environment. The visual feedback based manipulation aid constrains the motion of the virtual object as if it were moved in a real environment. Furthermore, in simultaneous correspondence with the visual constraints, the haptic feedback based manipulation aid constrains the motion of the user's hand in the real environment. The proposed method introduces a magnetic metaphor: the user has the sensation of manipulating a virtual object on a rigid surface without using a large and powerful robot arm and the time consuming simulation of detailed physical phenomena. The properties of this manipulation aid based on two kinds of feedback are discussed. Experimental results show the effectiveness of our proposed method.

Keywords: Virtual Environment, object manipulation, manipulation aid, haptic feedback, visual feedback

1. INTRODUCTION

In the ultimate virtual reality system that generates perfect stimulus for all of the user's senses, a user could manipulate a virtual object as well as s/he could in the real environment (RE). To simulate comprehensive physical rules in the virtual environment (VE), the system requires costly calculations and simulations: the avoidance of intersection among virtual objects, the fall of a virtual object caused by gravity and friction between virtual objects. Additionally, generating whole stimulation requires special display devices for visual, auditory and haptic sensations. Therefore, it is difficult to realize a perfect VE.

The simplest VE using a typical VR system (a HMD and a glove-like device) requires a user to exercise skillful operation for even a simple pick and place task. When s/he penetrates a block on a table in VE by the simple VR system, it cannot present feelings of collision that are presented to the user as direct feedback of the involuntary hand motion. Thus, s/he has to pay much attention to controlling all motions of a block in manipulation. Of course, some motions are naturally restricted in the RE, but the system needs a lot of resources for such realistic physical behavior in VE. This is one of the main reasons why the simplest VR is not commonly used in daily work as is a 3D CAD.

Here we are interested in object manipulation in the VE. A useful way to provide as natural sensation for precise and natural manipulation as in RE is to restrict the excessive degrees of freedom (DOF). That is, the system creates a virtual ruler in the VE.

There are many approaches to creating a virtual ruler. Most of them can be classified into haptic and visual approaches. The first method, named "Haptic feedback-based manipulation aid", physically restricts the motion of the user's hand in the RE by using a special master manipulator called force display. In the previous example, the system prevents the user's hand from sticking onto the table physically in RE. Using an ideal force display, there is no difference from manipulation in RE. The other approach, named "Visual feedback-based manipulation aid", visually restricts the object's motion in the VE. Here, when the handled object collides with another one, the motion of the handled object is retouched to prevent geometrical contradiction in VE. The simulator of the VE does not deal with complex and time consuming accurate physics of the object, so it can be put to practical use in recent VR application.

In this paper, we propose a combination of visual and haptic feedback based approaches. In a haptic feedback based method, an Ideal force display has to have a powerful enough reaction force, low mechanical friction and more than six DOF motion (three for translation and other three for rotation). This means that the higher-quality force display becomes more complicated. On the other hand, the visual based system ignores a part of the user's motion, so there is a discrepancy in operation. Moreover, the user depends on the object's visual reaction to recognize the status of manipulation. This often causes incorrect operation.

The proposed method used each approach to compensate for the disadvantages of the other. The method introduces a magnetic metaphor in visual and haptic feedback to restrict the motion of the handled object and the user's hand. This trial system reduces the contradictory effects of using direct and involuntary feedback, so it allows the user to penetrate an object on a table dexterously without high level of skill, the same as in the RE.

In the following section, the properties of these manipulation aids are discussed and a trial configuration is introduced. Experimental results show the effectiveness of our proposed method, which uses both visual feedback and haptic feedback based manipulation aids.

2. MANIPULATION AID USING VISUAL AND HAPTIC FEEDBACK

2.1 Assistance for object manipulation

When an object has no intersection with other objects in a RE, it can be freely moved and rotated in any direction by the user. When the object is placed on the surface of another object, its motion is physically restricted. To illustrate these fundamental properties, consider the simple task of aligning cubes on a table. A cube has six planar sides that are perpendicularly connected. Ignoring rolling off a table, the DOF of a cube placed on the table is reduced to three (two translation and one rotation.)

In a VE, the motion of a user's hand is usually reflected in the motion of the handled cube. As mentioned in first section, ideally it is necessary to reduce the DOF of both the user's hand and the cube to precisely place the cube on the desk in the VE. From this point of view, the properties of visual and haptic feedback based manipulation aids are first explained in full. Then we will propose an effective combined method.

2.2 Visual feedback based manipulation aid

The simplest approach to support the accurate positioning of objects in a VE is to use visual constraints among objects. This restricts the object's motion but does not restrict the user's hand motion, so there is discrepancy between the actual user's hand and the displayed object's position and orientation. An illustration of this approach is shown in Fig. 1-a. The original DOF of the virtual object is six, but DOF is restricted to three when the object is placed on a table. The actual sensor position and orientation of the object are controlled by the user's hand input. The displayed object position is modified after constraints are applied. Fig. 1-b shows a sample manipulation using this method. Although the image of the statue is stood straight on the desk, the line drawing statue indicates the real position of the hand.

Much literature is devoted to visual feedback based approaches (Baraff 1989, Chanezon 1993, Fernando 1993, Kijima 1995, Snyder 1995), but a user may have a sense of incompatibility caused by the difference between visual feedback and kinesthetic sensation. The key solution in this approach concerns how the manipulation aid modifies object position to provide intuitive and compatible assistance to the user while the handled object interacts with other ones.

The drawback of incompatibility is reduced by using a 'magnetic metaphor' to express the state transition of objects (Kitamura 1995). The handled object visually behaves as if it is attracted by a pseudo magnet on the face of an object. When exiting from the aided condition, the user feels as if s/he detaches the pseudo magnet. Although the magnetic metaphor solves the above drawback, it only visually simulates the dynamics of the objects. This means that a geometrical contradiction still remains, and that the user has to monitor the aided condition in some way.

2.3 Haptic feedback based manipulation aid

The haptic feedback based approach applies a physical limitation on the user's hand by a force display (Brooks 1990, Koutoku 1994, Ishii 1993, Iwata 1990, Noma 1993). When the user puts an object on a table in the VE, the system detects a collision between the object and the table in the simulation and then the force display presents a suitable reaction force to the user's hand.

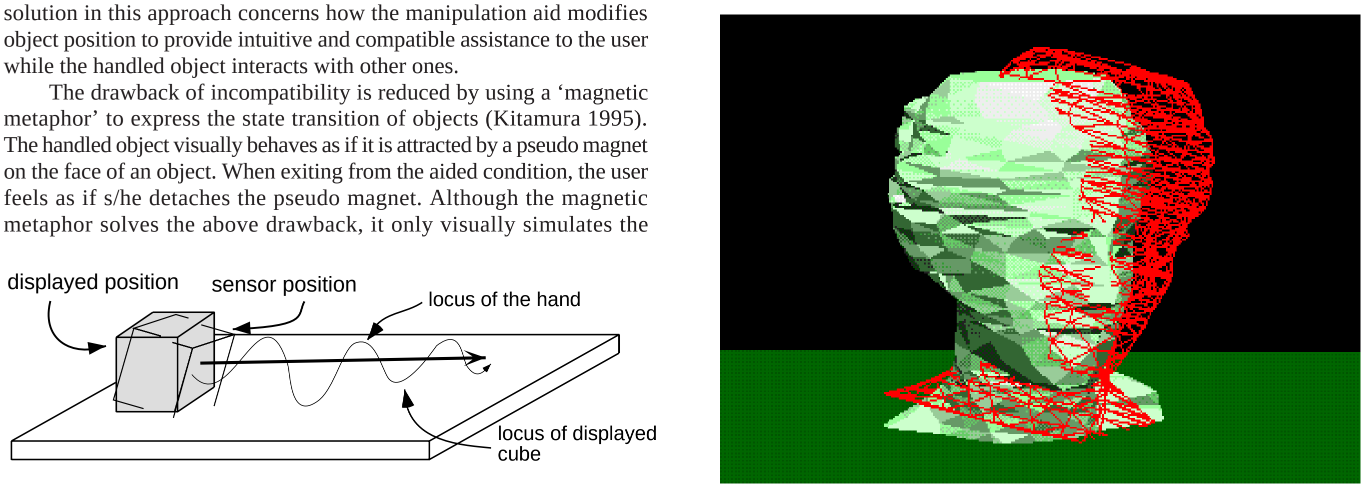
Previously such haptic feedback systems have been studied in robotics as a master-slave system. Their goal has been to realize an exact physical simulation of a slave arm on a master manipulator in a RE. Such a system requires that the robot arm suppress the human muscles, so its design has been large and powerful. Additionally, a physical model introduces spring and damper based physics, so it needs a high-speed feedback controller to avoid vibration in simulating a rigid surface.

As mentioned in the first section, the force display has to follow the user's motion in the entire working area and generate enough reaction force to restrict the user's motion to our purpose. Therefore, as with the master-slave system, the force display has to be designed as a large and powerful device with enough DOF and movable volume. However, it is hard to design such an ideal force display because of the physical limitations.

The force display shown in Fig. 2 is used in a trial system in a later section. Although we have designed it as a desktop force display and it is adequate for this purpose, it is insufficient for more general application. This force display has three actuated joints to generate a reaction force at the grip on the end of the display, where it generate maximum 10 N reaction force. It is insufficient to present a highly stiff surface for more general purposes. Moreover, the grip is connected through unactuated three axis universal joints, so it can follow and measure a six DOF motion of a user's hand but cannot physically restrict rotational motion.

2.4 Combination of the visual and haptic approaches.

As mentioned above, each of these two methods has its own disadvantage. The proposal method can complement each method's disadvantages with the other's by using both visual and haptic feedback based manipulation aids. Such an approach allows a user to manipulate a



(a) Concept of the visual constraint **(b) Example in the Virtual Environment**

Figure 1: Constraints of object's motion by the visual feedback based manipulation aid

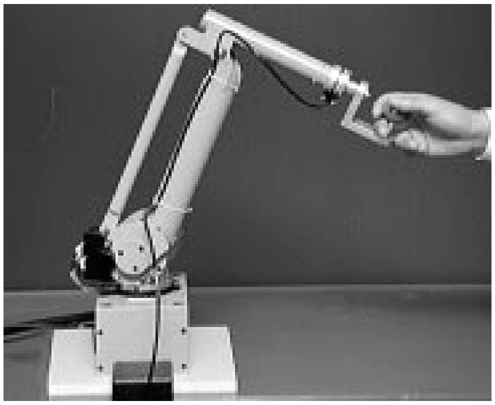


Figure 2: The force display with TOCUS

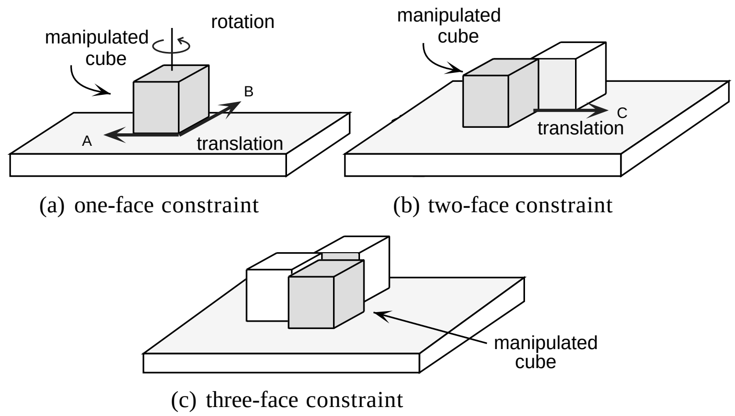


Figure 3: Constraints among faces for object manipulation

virtual object precisely and naturally with these limited resources.

As the visual approach introduces a magnetic metaphor, the reaction force acts not as a rigid surface simulator but as a direct indicator of the manipulation mode to haptic sensation.

When the handled object is restricted on one face, the reaction force is proportional to the distance of the object from the restricted face. In short, the user's hand is kept around the face without the user's conscious motion control. This simulates an elastic surface, so the highly stiff force display is not necessary.

Naturally, the direction of the constrained object is determined from geometrical conditions, so the user controls only unrestricted rotation of the object on the face. This means that the force display does not need actuators to restrict the hand's rotation.

When the user intends to pull the handled object from the face, s/he has to intentionally pull it against the reaction force. Moreover, the displayed object is stood straight on the surface visually, so this method is expected to reduce discrepancy between the haptic sensation and the displayed object's motion so that the user feels that s/he is manipulating a virtual object on a rigid surface. The point is that these feedback methods provides highly direct manipulation, so the user can focus attention on only manipulating the object's unrestricted DOF.

The mechanism is described in greater detail in a later section.

3. METHOD OF MANIPULATION AID ON A TRIAL SYSTEM

3.1 Overview

The trial system is described in this section. In this VE, all objects are modeled as polyhedra (boundary representations), are rigid (non-deformable), and can be concave or convex. We do not calculate and simulate the fall of virtual objects caused by gravity and friction between objects.

The proposed method is a technique that restricts the motions of the user's hand and the handled object. For simple objects that have faces perpendicularly connected, we consider three kinds of constraints as shown in Fig. 3. In the (a) one-face constraint mode , the object has one constrained face and the motion is constrained to three DOF: two translations on the planar of the target face and one rotation around the normal of that face. In the (b) two-face constraint mode, the object has two constrained faces and motion is constrained to one DOF translation along the two faces. In the (c) three-face constraint mode, the object has three aided faces; thus, there is no DOF when the object remains constrained to all three faces.

3.2 Real-time colliding face detection.

In order to flexibly apply a manipulation aid method that uses the constraints among faces to an assembly task that uses multiple objects with complicated shapes, it is necessary to dynamically detect constraining faces according to object motion rather than to limit detection to predefined faces in advance. For this purpose, the method has to detect collisions or interferences among objects. In this paper, we use a method of real-time colliding face detection for polyhedral objects with complicated shapes (Smith 1995). This method can detect colliding pairs of faces within 70 milliseconds when the objects have less than 4000 faces.

3.3 Visual feedback based method

The basic flow of visual feedback based manipulation aid is shown in Fig. 4, and only the essential points are discussed in this subsection.

3.3.1 State transition to constraint

An object with a complicated shape may have a number of colliding face pairs detected by the above collision detection stage. By examining the geometry between collision pairs and the speed of interaction, the face to be constrained can be dynamically selected. If a new constraint face pair is found, the displayed object position is modified to reflect the new aided position. Translation and rotations are applied to the object to move the selected face in a parallel manner onto the constraining face. The constrained faces for both objects change color.

The motion of the manipulated object is constrained on the faces. In the one-face constraint mode, the constrained translation is determined by projecting the change in the translational hand motion vector (sensor data) onto the planar of the target face. The constrained rotation angle is determined by using the change in angles of hand motion (sensor data) and the direction of rotation. In the two-face constraint mode, the constrained translation is along a vector orthogonal to both constrained face normals.

3.3.2 Release from constraint

Since the visual approach uses an intuitive magnetic attraction to constrain an object, the method for releasing the object from a constraint

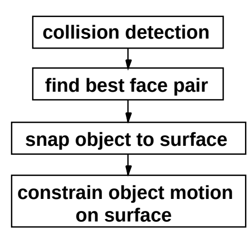


Figure 4: Flow of visual feedback based manipulation aid

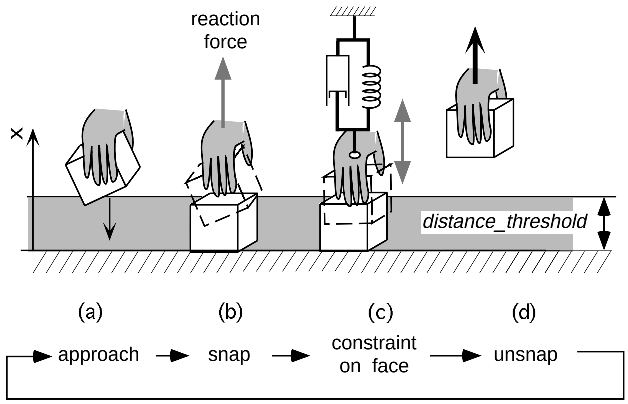
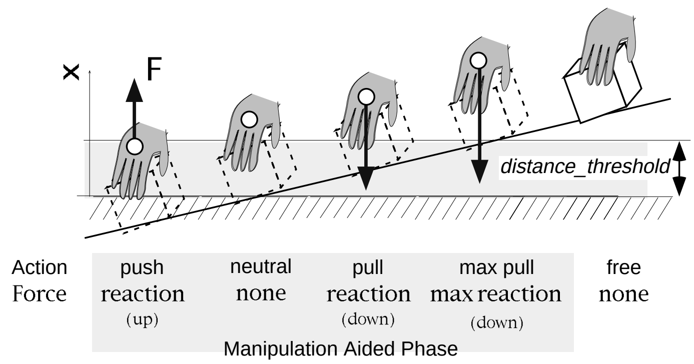
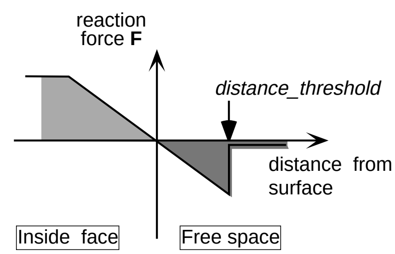


Figure 5: State transition and presentation of haptic sensation in manipulation



(a) Reaction force with one-face constraint



(b) Distance versus reaction force

Figure 6: Relationship between distance from the constrained face and generated force

is also intuitive. The release action is like unsnapping something from a magnetic surface. There are two conditions under which a constrained object may unsnap from a face: overlap ratio and distance from face. Satisfying either of these conditions is sufficient for an unsnap.

[Overlap Ratio]

The overlap ratio is the ratio of overlap area of the area of the two faces to the smaller face. If this value is less than the *overlap_threshold*, then the manipulated object unsnaps from the face.

[Distance from Face]

The distance-from-face condition uses the distance of the grasped position to the constrained face of the target object. When this distance becomes larger than *the dist_threshold*, the manipulated object unsnaps from the constrained face. Here, *dist_threshold* is a dynamic threshold that varies with the overlap area given by

$$dist\_threshold = k\sqrt{A} \quad (1)$$

where A is the overlap area and k is a positive parameter. Therefore, we assume that the greater the contact area, the greater the distance required to unsnap from the surface.

3.4 Haptic feedback based method

3.4.1 Haptic representation of state translation

The haptic feedback is designed to allow a user to perceive the mode shift unconsciously with haptic sensation. Fig. 5 shows the relationship between the manipulation phases and the haptic representation of each phase.

When the system detects no constraint, the force display releases all joints and the user has no physical restrictions. When the phase is shifted to snap (from (a) to (b) in Fig. 5), the force display locks all joint of the force display in a short time and displays an impact on the hand to stop motion.

While the object is constrained on the face (Fig. 5 (c)), the force display simulates a spring and damper system in the vertical direction of the constrained face.

As mentioned above, the magnetic metaphor is also introduced in haptic feedback. When a real magnet placed on metal is pulled off at a certain point, it generates as much reaction force as applied force. When applied force exceeds a threshold, the magnet is suddenly separated from the metal.

In our technique, the same behavior is utilized. One different is that the reaction force is proportional not to the applied force but to the distance from the face. As the user's motion along to the restricted direction is not visually reflected while manipulation is aided, the reaction force acts to reduce the geometrical inconsistency between the user's hand and the restricted object, as shown in Fig. 6(a) and (b). It must be noted that although the user's hand roughly moves above and below the constrained face, the user does not have to pay strict attention to keeping his or her hand within the *dist_threshold*.

As mentioned above, when the inconsistency is larger than *dist_threshold*, the manipulated object is unsnapped from the constrained face. The force display applies maximum attracting force at the *dist_threshold*, and when the object is unsnapped this reaction force is suddenly cut off. This means that the user must consciously tear off the object against the force when s/he wants to unsnap the object.

3.4.2 Force display with TOCUS

The force display shown in Fig 2 is actuated by custom-made torque controllable ultrasonic motors (TOCUS). The TOCUS is driven by frictional force and is completely different from the typical electric magnetic motor (EMM) used in many fields. TOCUS has many features, the most interesting of which is its ability to act as both a motor and a brake.

Fig. 7 shows the principles of the TOCUS. The TOCUS consists of a rotor and a stator. A piezo-electric device and an elastic material are mounted on the surface of the stator. The rotor is pressed against the stator with a spring. In the power-off mode, as the surface of the elastic body is glued to the rotor, the TOCUS acts as a brake (Fig. 7-a). When two synchronized sine signals are supplied to the piezo-electric device, the piezo-electric device and the elastic body vibrate together in the vertical direction. Under this condition, the sustaining torque is reduced (Fig. 7-b). The grade of deformation is in proportional to the voltage of the supplied signals. In our TOCUS, this control mode is used to control the sustaining torque.

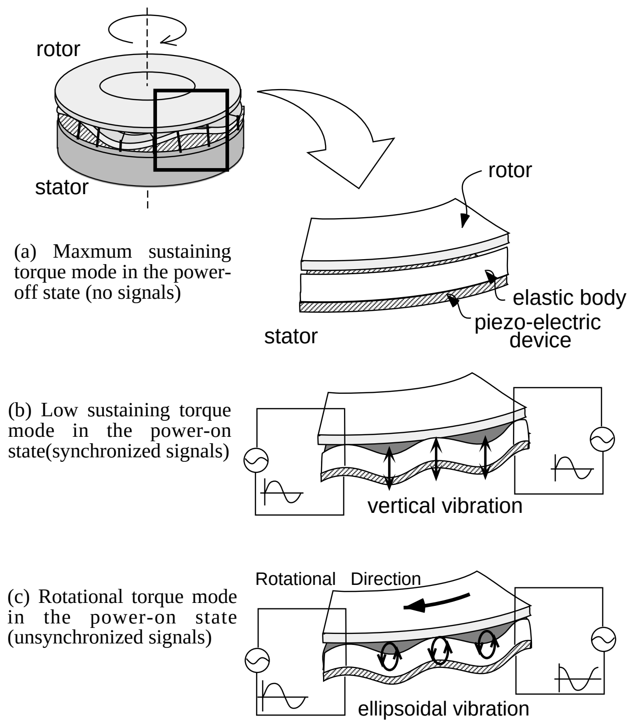


Figure 7: Torque controllable ultrasonic motor

When two sine signals whose phases are shifted 90° apart are supplied to the piezo-electric devices, the surface of the elastic body rotates elliptically and the traveling wave is raised on the stator (Fig. 7-c) The traveling wave generates a frictional force. The frictional force depends on the velocity of the traveling waves, so it can be controlled by the distance the two signals' ϕ are phase shifted apart.

Additionally, it has a light and compact structure. It can generate twice as much reaction force per unit weight as a typical EMM. It works most effectively and silently at low speed. This gives the TOCUS an advantage over the EMM as an actuator for a force display. Furthermore, as TOCUS is driven by a frictional force, it almost never generates magnetic noise. This means that the TOCUS never disturbs the electromagnetic field of the magnetic positioning sensor that is widely used in VR-systems.

4. EXPERIMENTAL METHOD

Two experiments were conducted to examine the features of the haptic and visual feedback based manipulation aid and to determine the effectiveness of the proposed method.

4.1 System for virtual object manipulation

Fig. 8 shows the hardware configuration of the experimental system. All input and output devices and sensors were controlled by the SGI ONYX™ workstation. Two 70-inch CRT projectors were used to present position-tracked stereoscopic images. User eye position was derived from the Fastrack™. Accordingly, the system could present nondistorted images with depth sensations and motion parallax. A user can grasp and manipulate objects with his or her hand by using the Fastrack™. At the same time, the user feels the reaction force provided by the force display to simulate magnetic attraction. In addition to visual and haptic feedback, a MIDI sound generator makes a wooden knocking sound when objects are snapped together.

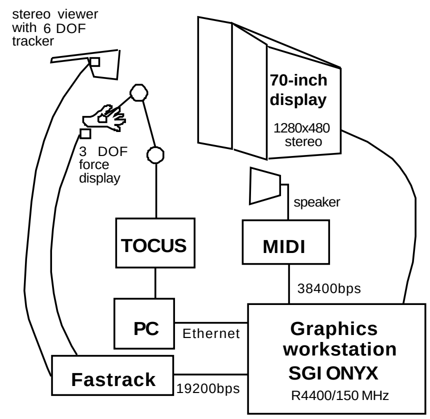


Figure 8: Hardware setup for virtual object manipulation using visual and haptic feedback based aid

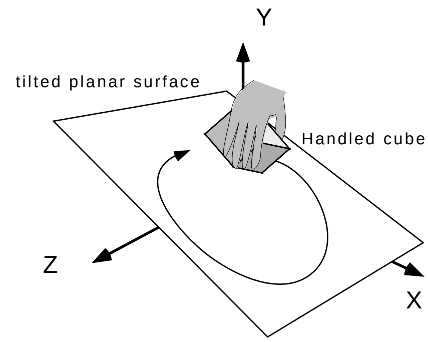


Figure 9: Experimental setup measuring distance difference during object manipulation on a planar surface.

4.2 Mode definition of manipulation aid

In the following two experiments, virtual object manipulation and placement, each of the following four modes are compared.

- **Mode V**: With visual feedback based manipulation aid, but no haptic feedback based manipulation aid.
- **Mode F**: With haptic feedback based manipulation aid, but no visual feedback based manipulation aid.
- **Mode VF**: With both haptic feedback based manipulation aid and visual feedback based manipulation aid.
- **Mode NO**: No manipulation aid. This is the same as the simplest VR configuration with 3D glasses and a glove-like device. This mode is used for reference.

4.3 Exp.1: Object manipulation on planar surfaces

An experimental method to measure the discrepancy during object manipulation on a planar surface is described. The purpose of this experiment was to confirm the effectiveness of the proposal manipulation aid while the handled object is restricted. Subjects were asked to move a 7 cm cube on a tilted planar surface for about 20 seconds as fast and precisely as possible under the one-face constraint as shown in Fig. 9. All users were tested on four tilted target surfaces with four manipulation modes. Here, the discrepancy between the position of the hand (sensor position) and the constraining surface is measured.

4.4 Exp.2: Object positioning task

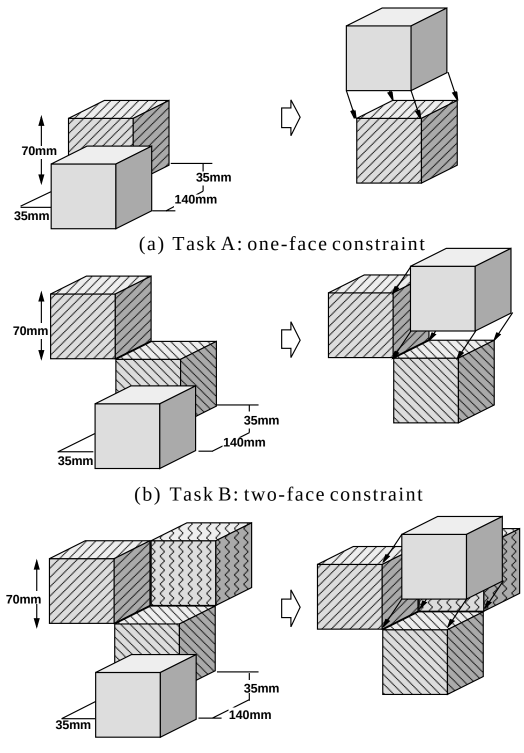


Figure 10: Experimental tasks for accuracy evaluation

An experimental method was used to examine and compare the accuracy of object placement in each of the four modes with/without haptic and visual feedback based manipulation aid.

4.4.1 Task definition

Three tasks were designed for testing one-, two- and three-face constraint. Fig. 10 shows the task configurations.

Task A: One-face Constraint — consists of two 7 cm cubes that were initially separated in the horizontal and forward directions. The task is to place the front cube on top of the other cube, aligning all four corners of the faces, as shown in Fig. 10(a).

Task B: Two-face Constraint — consists of three 7 cm cubes; two of the cubes share an edge and form a right angle surface, and the third cube is initially separated from the lower cube as in the above task. The task is to place the third cube into the space between the right angle surfaces formed by the other two cubes, aligning all six vertices, as shown in Fig. 10(b).

Task C: Three-face Constraint — consists of four 7 cm cubes; the same configuration as for task B but with a fourth cube having shared edges with the previous two cubes, forming a right angle corner. The task is to place the forth cube into this corner, aligning all seven vertices, as shown in Fig. 10(c).

4.4.2. Experiment

The purpose of this experiment was to compare the accuracy of object placement in each of the four modes previously described. Subjects were asked to complete tasks A, B and C as accurately and quickly as possible. Ten trials were done for each mode and task. In this experiment, three measurements were taken: task completion time, distance accuracy, and angular accuracy. The task completion time was the time between

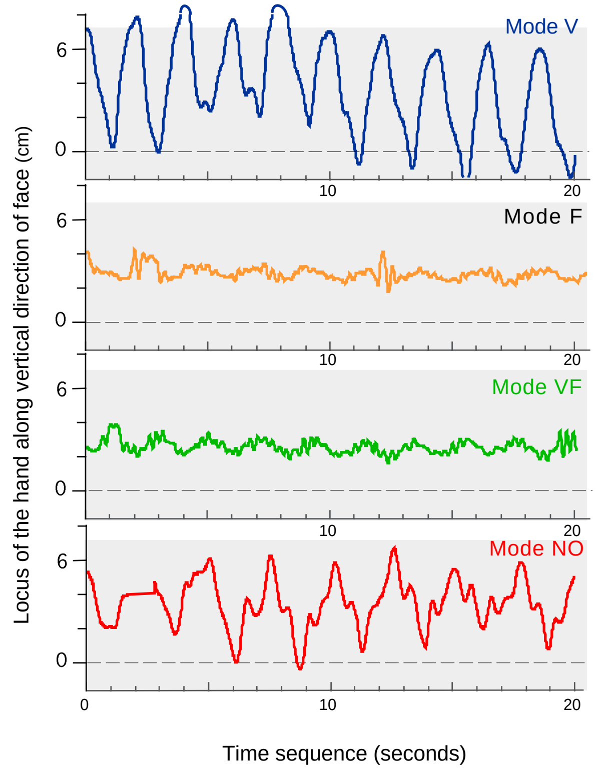


Figure 11: Typical locus of the hand along vertical direction of constrained face during object manipulation on planar surface

object grasp and release, as measured by a computer real-time clock. Each task consisted of one object grasp and one release; accordingly the user could not readjust the object after it had been released. The distance accuracy was the sum of the distances among the four, six or seven vertices of the cubes in tasks A, B and C, respectively. The angular accuracy was the sum of the three angle errors (azimuth, elevation and roll) from the target position.

5. Results and discussion

This section describes experimental results and considerations of two experiments.

5.1 Results of exp.1: manipulation on a constrained face

Fig. 11 is a time series graph that indicates the distance between the actual user's hand and the target planner surface while the cube is moved on it. The cross-dot line at zero indicates that the cube is just on the face. The result depends on whether the haptic feedback based method aid is used.

In the group without the haptic approach, when the cube is restricted on the constrained face in the V mode, the users did not have to pay so much attention to operation. On the other hand, in the NO mode, the subjects had to always adjust the whole cube's motion, as shown in the result. Consequently, the width of the distance error in the V mode is larger then in the NO mode.

The results with F and FV showed less distance error and less width of vibration than with the V and NO modes. This means that the reaction force allowed the subjects to move the cube near the surface. The loci of F and FV, however, look almost identical in the result. In the

Table 1: Standard error of distance between actual hand position and constrained face during object manipulation on planar surfaces

Task mode	Plane surface A	B	C	D
V	2.3	3.2	3.0	1.5
F	0.5	0.9	0.5	0.5
VF	0.7	0.9	0.5	0.7
NO	1.2	1.8	1.3	1.3

(cm)

configuration, both modes used the same haptic feedback model, so that there is no difference in the loci. The difference in them depend on whether the cube was visually restricted in the surface; therefore, the handled cube was swinging on the surface as it directly followed the swinging user's hand motion in mode V. Furthermore, this haptic feedback cannot reduce the offset in the mode. We assumed that this is because a small force was absorbed by the inertia and the viscosity of the force display. Therefore a small reaction force is always used as a clue for manipulation. Even so, the cube in the mode VF is stood always straight on the surface.

Although the graph is a typical result from one subject, all subjects indicate almost the same tendency, that is other subjects showed nearly the same results. Table 1 indicates the standard errors of the distance from the results of all subjects for four surfaces (A, B, C, D). It was found that the haptic feedback based method (F and FV) could reduce vibration during manipulation. As for modes V and NO, the amount of error in mode V is larger than in mode NO. Therefore, we assumed that the user could manipulate an object easier in mode V than in mode NO, however, as mentioned above, this may lead to unsatisfactory operation such as sudden unsnapping of the object. Finally, it was concluded that

Table 2: Averages of position and angular error for tasks A, B and C from all subjects

Task	Mode	Positional error (mm)	Angular error (deg)
A	V	11	0.8
	F	20	4.0
	VF	9	0.8
	NO	19	4.0
B	V	15	0.0
	F	31	2.6
	VF	14	0.0
	NO	34	2.8
C	V	0	0.3
	F	29	3.2
	VF	0	0.3
	NO	38	3.2

mode FV has the advantages of both the visual and haptic feedback based manipulation aids.

In this experiment, we focused on the distance discrepancy of the user's motion to evaluate the proposed method. We should focus on subjective and physiological accepts in future work.

5.2 Results of exp.2 : the object arrangement

5.2.1 Accuracy of the arrangement

We used five subjects for this experiment, each of whom had sufficient training before the experiment. Fig.12 (a) and (b) show final position and angular error versus task completion time for task A (one-face constraint) of one subject. Results show that positional error and task completion time depended on whether visual feedback based method is applied. The subject could complete a task in mode F faster and more precisely than in mode NO. However, their performances were worse than with modes V and VF. This is because that the subjects feel only a small reaction force around the goal in these configurations. Furthermore, the force display could not restrict rotational motion, so the angular error

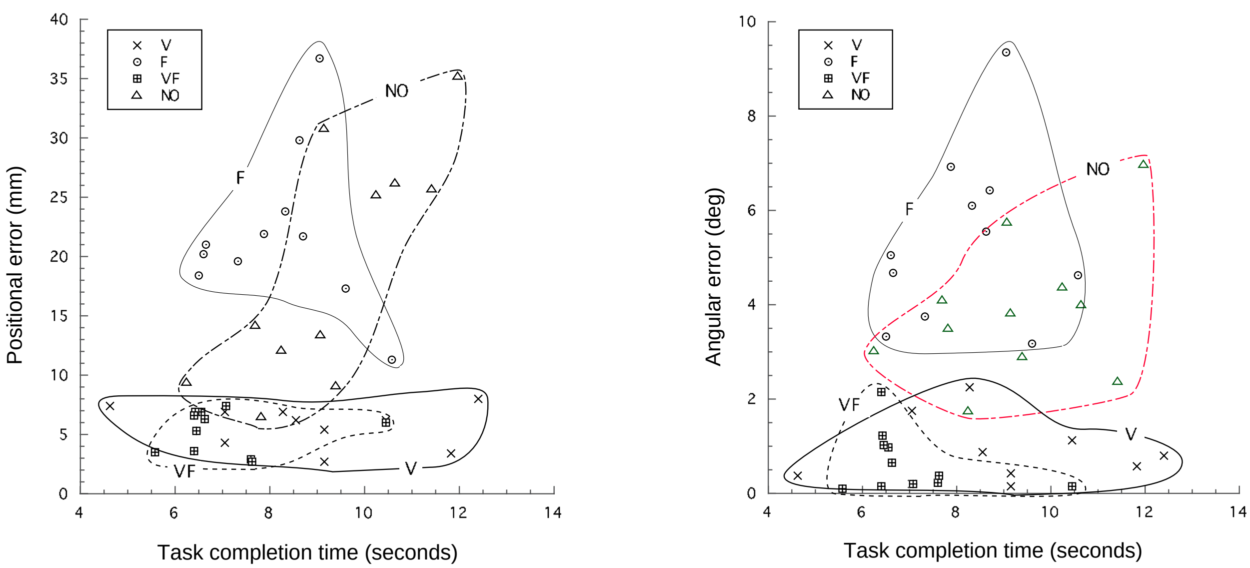


Figure 12: Positional and angular error versus task completion time for task A of one subject

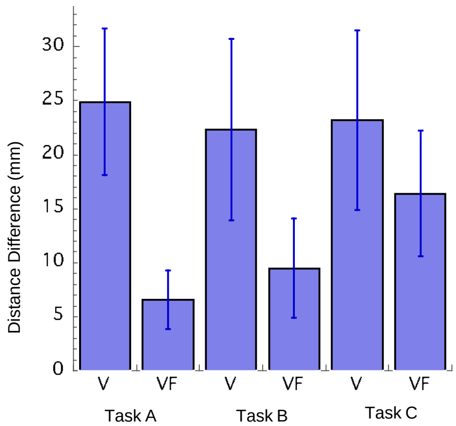


Figure 13: Average and standard errors of distance difference of tasks A, B and C for all subjects

in F mode is no different from the error in NO mode. These problems were solved by the visual feedback based method. In other words, the subject could achieve higher precision in a shorter time with the visual feedback based method. Comparing modes V and FV, results show that task completion time in mode FV was shorter than in V, but there was significant difference in the errors.

Table 2 shows the average positional and angular errors for all tasks from all subjects. In every task, each subject could get more precise results in V and VF modes than in F and NO modes.

5.2.2 Distance and Angular difference

Next, we focused on the difference between V and VF modes. Fig. 13 shows averages and sampling errors of the positional difference between the actual hand position and the retouched object position in tasks A, B and C of all subjects. In all manipulation modes, the positional difference in mode VF is smaller then in mode V. This means that the method with both visual feedback and haptic feedback can allow a user to precisely manipulate an object without much discrepancy.

Angular difference was measured in the same way. Since the system does not restrict rotation, there was no meaningful difference in the results.

6. Conclusion

This paper proposed a new method of object manipulation in a VE using visual and haptic feedback based manipulation aids. Although the trial system employed a six-DOF force display, only three of them were actuated for translation. This means that the force display did not restrict rotation of the user's hand. The visual feedback based manipulation aid can support this insufficient DOF. On the other hand, the haptic feedback based manipulation aid can reduce the discrepancy between the actual user's hand and displayed object position. Using the proposed method, the user's hand could always follow the constrained object motion. Experimental results confirmed that the system allows the user to precisely and intuitively manipulate the object in the VE.

It is expected that our method will make the user believe that s/he is manipulating a virtual object on a rigid surface without the use of a large master arm and the time consuming simulation of detailed physical phenomena. This method can be easily applied to the many fields such as a 3D-CAD and 3D simulation. In future work, we should confirm which factor is most effective in this configuration. Also, we should introduce another sensing channel. In this configuration, the system always used the same sound to indicate collision between objects. Sonic sensation has many unique features and can indicate the condition of impact and the material of the object. Therefor it is expected to increase the intuitiveness of the VE.

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