A Proposal of a Clutch Mechanism for 6DOF Haptic Devices

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Abstract

This paper describes a new clutch mechanism named "Dual Shell Method" which enables the users to intuitively operate a pointer in VR space. It is so named because it is comprised of two shells, with a small shell inside a larger one. Both shells' center positions correspond to the center of the interface device. This system changes clutch state according to grip position of an interface device. First, grip position in device space and the pointer in VR space are connected. In this state, the clutch state is ON. If the grip reaches the outer shell, which is the edge of the interface device, the clutch state turns OFF automatically. Then the grip and pointer are no longer connected. To turn the clutch state ON, a user is required to move the grip into the inner shell. The "Dual Shell Methods" is more natural than manual clutching, because clutch state can be changed automatically, so user do not have to keep their attention on the device space. Results of the experiments conducted to assess the effectiveness of this method are presented.

1. Introduction and Related Works

Virtual Reality (VR) is a technology, which allows users to interact with a computer-simulated environment. VR environments are mainly visual experiences displayed on a computer screen. With the incorporation of tactile information, generally known as force feedback, to the VR environments, haptic systems started to appear. As the haptic systems enable a real-like force feedback to users, they are of a significant importance for medical, gaming and manufacturing industries, as well as for education and training.

To interact with VR world, usually 3D interface devices as shown in Fig. 1 are employed[1, 2]. Generally, these devises are used for linking the position of the interface device to the pointer in VR world. Position control is intuitive and good for accurate operation, but the limitation of the pointer area represents a major problem. As the position $\mathbf{p}$ of the interface device is limited mechanically, the pointer position $\mathbf{P}$ which is simply a mapping of $\mathbf{p}$ is limited as well.

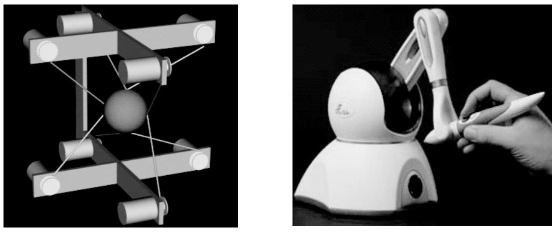

Figure 1. SPIDAR and PHANToM

Applying rate control is one of the possible ways to solve this problem. Rate control adapts device position to the velocity of the pointer movement $\mathbf{V}$ by an empirically selected constant, k. This relation is shown in Equation 1.

$$\mathbf{V} = k\mathbf{p} \tag{1}$$

Furthermore, the pointer position $\mathbf{P}$ is calculated by the integral of $\mathbf{V}$.

$$\mathbf{P} = \int \mathbf{V}dt = \int k\mathbf{p}dt \tag{2}$$

Equation 2 states that $\mathbf{P}$ is generated through an integral filter. Such a filter causes the user feel less intuitive than the reality. Besides, accurate controlling is relatively difficult [3, 4].

Addressing these problems, some mechanisms have been proposed. A first mechanism is based on a hybrid position/rate control[5], which is useful to interact with a large VR environment. However, it is less intuitive because of rate control. A second mechanism is based on the button clutching. We connected the new clutch system with an on-surface button to a SPIDAR-G[6] system. SPIDAR-G is selected for the application instrument, as it is not only a 3D translation device but also a 6 DOF (translation x,y,z and rotation around x,y,z axis) haptic interface device.

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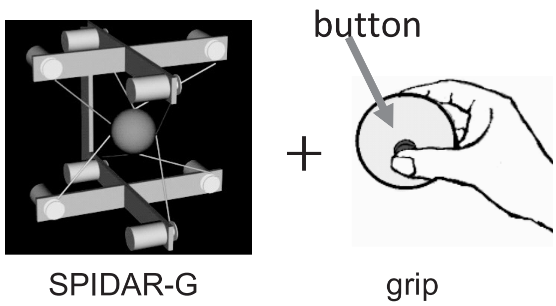

Figure 2. SPIDAR-G and button

The on-surface button is added to the proposed clutch system to get inputs from users (Fig. 2). By pushing the button, clutch state toggles between two different states. In this mechanism, users can use position control in a large scale VR environment. However, users have to check device grip position by watching or feeling their arms when they push the button.

In this study, we proposed a new clutch mechanism named "Dual Shell Method (DSM)", which provides the users with an infinite-like device space and an intuitive clutch feeling. These are made possible by changing the clutch state, position and orientation automatically. Results from a preliminary experiment suggest that our proposed method facilitates operation in VR space.

2. System Requirements

2.1. Do Natural Clutching

Mouse may be considered as the most common 2D interface device. They are easily controlled by position control, but the limitation of movement due to the limited size of the mouse pad constitutes a major problem. This problem is usually solved by lifting up the mouse, stopping the communication with the PC and placing the mouse on a more appropriate point on the pad. Although such a simple solution may be adequate for daily PC use, specialized haptic devices require a different perspective.

Compared to the mouse, the manual clutching might not seem natural, as its button is not intuitive enough. Mouse's lifting-up action is not difficult, and users can easily comprehend that action by themselves. On the other hand, pushing a button on SPIDAR-G grip is not a common process for users.

Not letting the users to notice the clutch operation is the first step for a successful design. To realize this goal, we modeled such a clutch system that switches the clutch state automatically based on the grip position in device space.

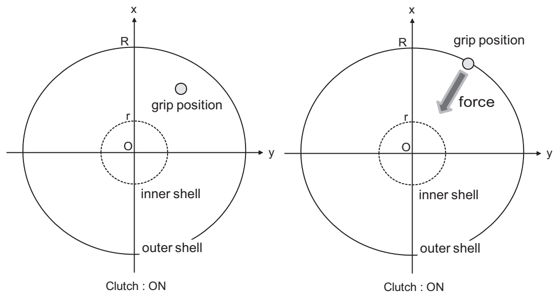

Figure 3. concept of DSM

2.2. Feel the device space

Users constantly have to check device grip position by looking at or feeling their arms. Then users have to move a grip to center. It refrains from their concentrations on the real task.

Perception of the device space is usually performed by looking at the device. However, it is possible to eliminate the need of this visual contact by taking advantage of haptic feedback. Users can percept the edge of the device space via an extra force (representing the haptic feedback). The direction of the additional force is not important, as it is applied for only a short period of time, and only when the grip reaches to the edge of device space.

3. Propose of Dual Shell Method

3.1. Dual Shell Method for Translation

On the basis of the previous proposal, we have a new controlling system named the "Dual Shell Method (DSM)". It is so named because it is comprised of two shells, with a small shell inside a larger one. Both shells' center positions correspond to the center of the interface device.

1. First, grip position in the interface device and pointer position in the VR world are connected (Fig. 3, left).
2. Second, if the grip reaches the outer shell, which is the edge of the interface device, the system informs the user by adding force for a short period. Soon, haptic navigation starts, adding force which guides the grip to the center of the interface device. Then the user is required to follow the force (Fig. 3, right).
3. Moving the grip to the center of the interface device, the grip returns to the inner shell. The system informs the user again by applying force for a short period. Then, the clutch turns ON automatically.

3.2. Dual Shell Method with high stroke

To improve the short stroke problem of DSM, we attempted to create a Dual Shell Method with high stroke. A

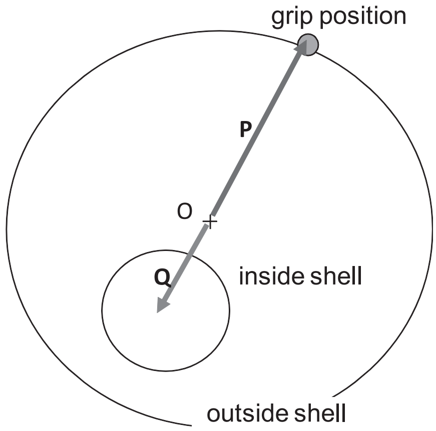

Figure 4. concept of DSM with high stroke

simple mechanism, the inner shell moves adaptively when the grip position reaches the outer shell and the clutch turns OFF.

We define the center point of the device space as the origin of coordinate space. The distance from the center to the outer shell in device space is R. The grip position when the grip reaches the outer shell is $\mathbf{P}$ ($|\mathbf{P}| = R$). As shown in Fig. 4, the center of the inner shell position $\mathbf{Q}$ is described by Equation 3.

$$\mathbf{Q} = -a\mathbf{P} \tag{3}$$

”a” is stroke number. A larger ”a” results in a larger stroke.

3.3. Dual Shell Method for Rotation

We propose extended version of DSM. SPIDAR-G sends the grip orientation information to PC as the quaternion. Quaternion $\mathbf{q}$ which rotating θ [rad] around rotation axes $\mathbf{v}$ ($|\mathbf{v}| = 1$) is described in Equation 4.

$$\mathbf{q} = \begin{bmatrix} cos(\theta/2) \\ v_x \cdot \sin(\theta/2) \\ v_y \cdot \sin(\theta/2) \\ v_z \cdot \sin(\theta/2) \end{bmatrix} \tag{4}$$

Moreover, initial orientation of grip is shown in Equation 5, as θ = 0 [rad].

$$\mathbf{q_0} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

This system needs only rotation angle θ [rad], then rotation axes is arbitrary. Here is the step-by-step explanation of the DSM-rotation:

1. First, grip orientation and pointer orientation are linked to each other.
2. If the grip rotates a certain amount θ_{max} around any arbitrary axis, system informs the user with a haptic force feedback, and clutch state toggles. The moment that force feedback is applied, haptic navigation starts by applying torque, which guides grip towards the initial orientation. During haptic navigation, user is required to follow the force.
3. Guided rotation continues until the theta angle of the quaternion reaches at the lower threshold value, named θ_{min}. When the rotation finalizes, user is informed by another short duration force feedback. Clutch changes to ON state automatically.

3.4. Dual Shell Method for 6DOF Operation

We also propose 6DOF version of DSM. The clutch state of 6DOF X is described in Equation 6.

$$\mathbf{X} = \mathbf{T} \cdot \mathbf{R} \tag{6}$$

”T” is the clutch state of translation, and ”R” is the clutch state of rotation. Thus, when both are ON, the clutch of 6DOF turns ON. Otherwise, the clutch of 6DOF turns OFF.

4. Experiment Evaluation

We have evaluated about the usefulness of proposal method. We compared 3 methods.

Method 1 : Using the keyboard space-key for changing clutch state.

Method 2 : Using the on-surface button of the grip for changing clutch state.

Method 3 : Using DSM.

SPIDAR-G was used as the interface device. The grip can move 5[cm] from the center of the SPIDAR-G frame. The radius of the outer shell is 5[cm], and the radius of the inner shell is 1.5[cm].

4.1. Experiment 1: Translation Operation

An experiment was performed to evaluate the translation operation of the Dual Shell Method.

4.1.1 Experimental Task

A box linked to the grip position is placed at the center of Fig. 5 and a target is placed at the back of the VR world.

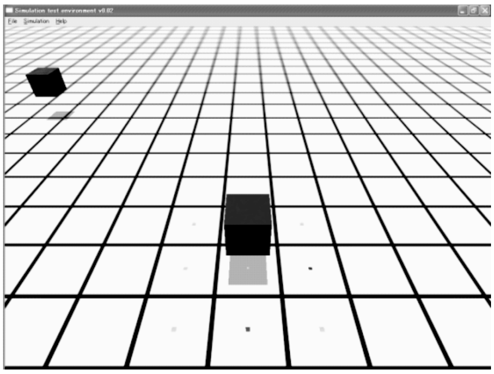

Figure 5. initial image

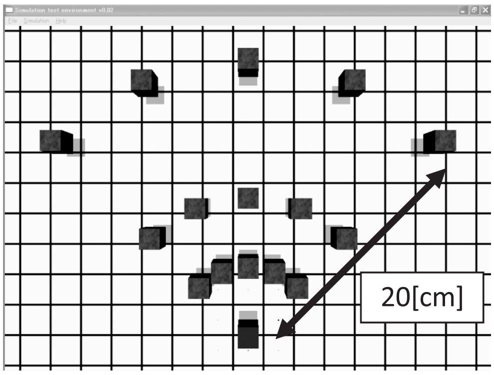

Figure 6. target position

Table 1. number of clutch times

target position	distance[m]	clutch times
FAR	20[cm]	4or5
MIDDLE	10[cm]	1or2
NEAR	5[cm]	no need

1. A pointer is placed at the center of the VR world. A target is placed at a randomly chosen position.

2. Move the object to the target and superimpose for 2[s].

3. The target is cleared and a new target is presented at the center of the VR world.

4. Move the object to the target and superimpose for 2[s].

Repeat steps 1-4 for 15 times.

Target position is decided in reference to the distance from the center position, where the object was first placed in the VR world, as shown in Fig. 6. And distance to target is decided in reference to clutch times which need to complete the task as shown is Table 1.

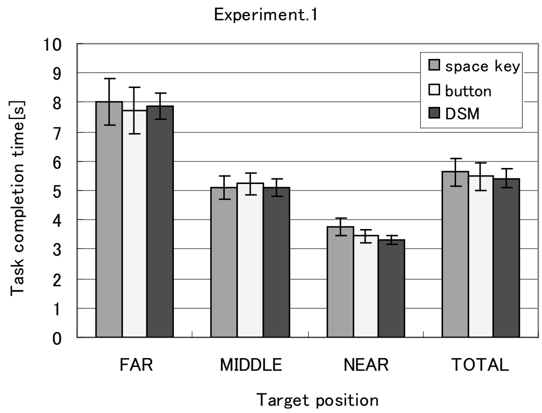

Figure 7. results of experiment

4.1.2 Results

5 subjects, 20-25 years of age, all male.

The horizontal axis is distance to the target. Vertical axis is completion time. Standard error (S.E.) is superimposed over average completion time.

Considering only completion time, the Dual Shell Method is not statistically effective.

4.2. Experiment 2: DSM with high stroke

An experiment was performed to evaluate translation operation of the Dual Shell Method with high stroke.

Method 1 : Using the on-surface button of the grip to change clutch state.

Method 2 : DSM (a=0.0)

Method 3 : DSM (a=0.4)

Method 3 : DSM (a=0.7)

Stroke number "a" is chosen as 0.0, 0.4, and 0.7 respectively.

4.2.1 Results

8 subjects, 20-25 years of age, 7 males and 1 female.

The horizontal axis is distance to the target. The vertical axis is task completion time. Standard error (S.E.) is superimposed over average completion time.

Results vary according to stroke number and distance to target.

For targets placed far, long stroke DSM (a=0.7) is superior to short stroke DSM (a=0.0). However, for targets placed near, short stroke DSM (a=0.0) is superior to long stroke DSM (a=0.7). In the total results, DSM (0.4) had the smallest compilation time, and the button method had

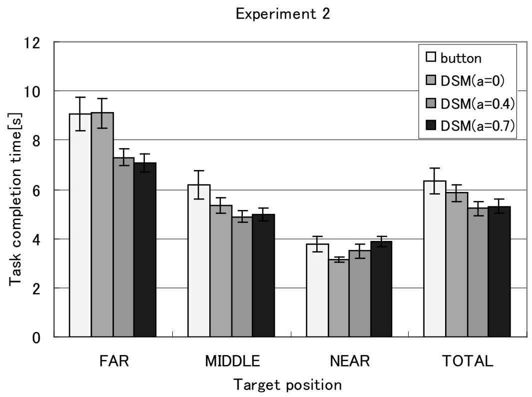

Figure 8. results of experiment 2

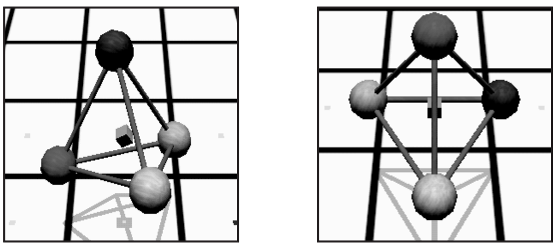

Figure 9. random(left) and initial(right) orientation

the worst. According to statistical analysis, DSM (a=0.4) is superior to the button method, with $\alpha < 0.01$.

4.3. Experiment 3: Rotation Operation

An experiment was performed to evaluate the Rotation operation of the Dual Shell Method.

4.3.1 Experimental Task

1. A pointer is placed at the center with initial rotation of the VR world. A target is placed at a randomly chosen orientation (Fig. 9, left).

2. Rotate the object to the target and superimpose for 2[s].

3. The target is cleared and a new target is presented with initial orientation (Fig. 9, right) of the VR world.

4. Rotate the object to the target and superimpose for 2[s].

Repeat steps 1-4 for 15 times.

Target orientation is decided in reference clutch times which need to complete the task, as shown in Table 2.

θ_{max} and θ_{min} was chosen as 90[deg] and 30[deg] respectively.

Table 2. number of clutch times

target orientation	angle[m]	clutch times
BIG	180 °	2or3
MIDDLE	120 °	1
SMALL	60 °	no need

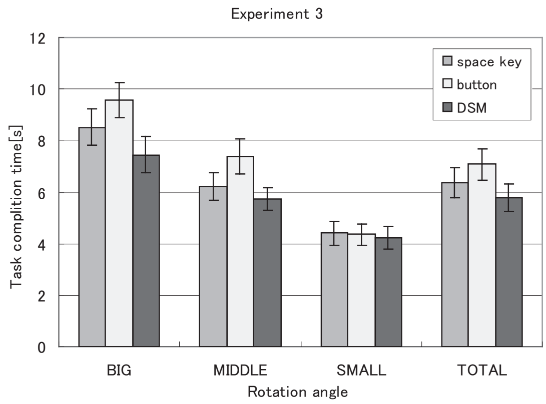

Figure 10. results of experiment 3

4.3.2 Results

10 subjects, 20-25 years of age, 9 males and 1 female.

The horizontal axis is distance to the target. The vertical axis is task completion time. Standard error (S.E.) is superimposed over average completion time.

Except for a small amount of rotation, button method's results were the worst. Moreover, DSM required the smallest amount of time to complete the test.

In the total results, DSM had the smallest compilation time, and the button method had the worst. According to statistical analysis, DSM is superior to the button method, with $\alpha < 0.10$.

4.4. Experiment 4: 6DOF Operation

An experiment was performed to evaluate the 6DOF operation of the Dual Shell Method.

4.4.1 Experimental Task

1. A pointer is placed at the center with initial rotation of the VR world. 10 targets are placed at randomly chosen positions and orientations (Fig. 11).

2. Translate and rotate the object to the target and superimpose for 2[s].

3. The target is cleared and a new target is presented with the next position and orientation of the VR world.

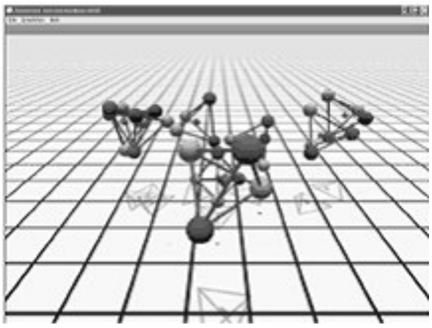

Figure 11. 6DOF task

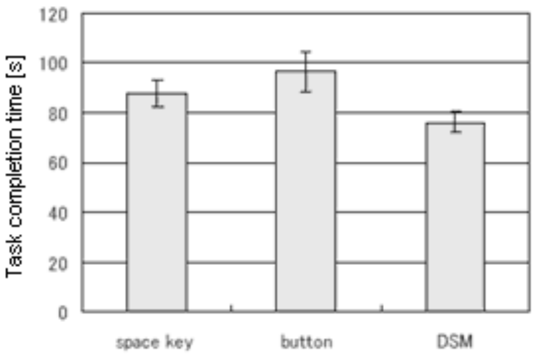

Figure 12. results of experiment 4

4. Translate and rotate the object to the target and superimpose for 2[s].

4.4.2 Results

10 subjects, 20-25 years of age, are all male.

Fig. 12 shows the completion time of each method. The vertical axis is task completion time.

In the result, DSM had the smallest compilation time, and the button method had the worst. According to statistical analysis, DSM is superior to the space key method, with $\alpha < 0.05$.

5. Discussion

5.1. Mistakes with Clutch Operation

In this section, we discuss mistakes with clutch operation and trajectory of grip movements in device space. Fig. 13 shows trajectory using Method 2 and Fig. 14 using DSM. The horizontal axis is time[s] and vertical axis is x-direction, the primary movement for completing the task. Rectangular waves represent clutch state, with upper values representing ON and lower values representing OFF. In Fig.

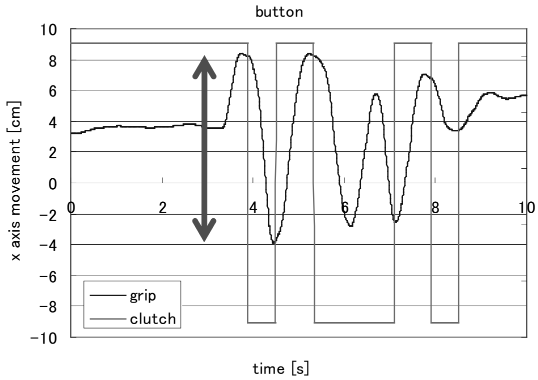

Figure 13. trajectory of grip : button

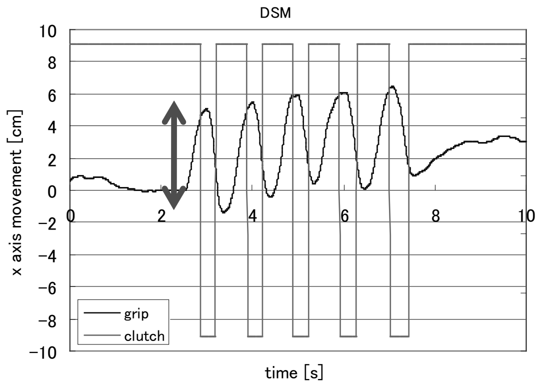

Figure 14. trajectory of grip : DSM

Table 3. clutch error rate

mode	clutch error rate[%]
space-key	24.5
button	19.0
DSM	5.8

14, it can be seen that the correct clutch state was used because the direction of grip movement at clutch state ON is different from that of clutch state OFF. However, in Fig. 13 at time 6[s], the user failed to operate the clutch properly in relation to trajectory. Clutch error rate is shown in table 3.

5.2. Strokes caused by clutching

We define the word "stroke" as the distance of movement of the grip made by 1 clutch operation. Observing the amplitude of trajectory (described by the length of the arrow) in Fig. 13, 14, the stroke for Method 2 is lower than that of DSM. But the trajectory for DSM shows more frequent moves. In the case of DSM, the grip moves a short amount, but frequently. In Method 2, the stroke is large, but the grip is moved infrequently. We conclude that DSM has a lower clutch error rate, but smaller strokes, and is not superior to other methods.

5.3. Why button method had the biggest completion time

It is because of the limitation of hand movement at varying rotation angles. It is hard for users to push the on-surface button while rotating the wrist. Therefore, users needed more time to push the button correctly.

5.4. Why DSM had the smallest time

For the DSM system, it is not possible to rotate the clutch more than a pre-defined threshold value, namely θ_{max}. If users exceed θ_{max} grip turns back to its initial orientation automatically. While limiting the rotation angle and rotating the grip to the initial orientation without any user support, we believe that the efficiency increases so that the required time to complete the task reaches a minimum value among all the three methods.

6. Conclusion

In this study, we proposed a new clutch mechanism, called Dual Shell Method (DSM) which provides its users with an infinite-like device space and an intuitive clutch feeling. These are made possible by changing the clutch state, position and orientation automatically. By increasing the amount of strokes, we improved DSM and had a better result than existing manual clutching. In addition, we found that there is a relationship between the movement of distance pointer and appropriate strokes. Finally, we extended Dual Shell Method for 6DOF operation. Conducted experiments showed that we had better results than the exiting manual clutching.

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