Abstract
In our research, we aim to construct a visuo-haptic system that employs pseudo-haptic effects to provide users with the sensation of touching virtual objects of varying shapes. Thus far, we have proved that it can be possible to modify an identified curved surface shapes or angle of edges by displacing the visual representation of the user’s hand. However, this method has some limitations in that we can not adapt the way of touching with two or more fingers by visually displacing the user’s hand. To solve this problem, we need to not only displace the visual representation of the user’s hand but also deform it. Hence, in this paper, we focus on modifying the identification of the size of objects handled with two fingers. This was achieved by deforming the visual representation of the user’s hand in order to construct a novel visuo-haptic system. We devised a video see-through system, which enables us to change the perception of the shape of an object that a user is visually touching. The visual representation of the user’s hand is deformed as if the user were handling a visual object, when in actuality the user is handling an object of another size. Using this system we performed an experiment to investigate the effects of visuo-haptic interaction and evaluated its effectiveness. The result showed that the perceived size of objects handled with a thumb and other finger(s) could be modified if the difference between the size of physical and visual stimuli was in the range from -40% to 35%. This indicates that our method can be applied to visuo-haptic shape display system that we proposed.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation (I.7)]: Multimedia Information Systems—Artificial,augmented,and virtual realities

1. Introduction
Haptics have become an important modality in recent virtual reality (VR) systems, and several haptic devices have recently been developed [MS94,HT99,Iwa01]. However, because it is difficult to perfectly reproduce the force that we perceive when touching an object, most haptic devices exhibit very complicated problems. As a result, it is difficult to apply haptic devices to widely used systems, because a large amount of preparation work, such as installation and calibration, must be performed for each user.

While research on haptic presentation in VR systems often concerns active haptics, an increasing number of works focus on alternative approaches such as passive haptics, which include pseudo-haptics and sensory substitution. Pseudo-haptics represent a kind of cross-modal phenomenon between our visual and haptic senses [LCK*00]. The pseudo-haptic approach is a potential solution for exploiting the boundaries and capabilities of the human sensory system to simulate haptic information without using active haptic systems. For example, when we are working on a computer, the slowdown of the cursor evokes a virtual frictional force on our hand holding the mouse. This phenomenon can potentially generate haptic sensations using only visual feedback, without the need to apply any physical devices.

In our research, we use this cross-modal effect to “change” the shape of an object, and construct a simple system that can display a variety of shapes, while the user touches only a simple static physical object (Figure 1). In other words, by using a visual display and physical device, we aim to exploit visual feedback to widen the range of what can be physically represented by the device. This system evokes a pseudo-haptic effect by controlling the displacement of a user’s hand in the image showing the user touching...
Using our system, we aim to display complicated shapes that are composed of primitives. Our system concept is presented in Figure 2. To realize this concept, we must develop two capabilities. First, we need to display primitives (i.e., convex, edge, concave, etc.) near the point of contact. Second, we need to set the relative postures of these primitives with an object. By combining these two capabilities, we can exploit the pseudo-haptic effect and display various shapes without applying any physical devices.

First, we used our simple system to confirm the possibility of displaying primitives of areas touched by the user. In particular, we proved that using the pseudo-haptic effect, users can perceive a variety of curved shapes, while touching only a physically static cylinder [BKN∗12b].

Second, we examined the possibility of exploiting the pseudo-haptic effect to modify an identified placement, especially the angles of primitives. The result of this experiment proved that the perceived angles of edges can be modified if the difference of angles between edges is in the range of $-35^\circ$ to $30^\circ$ [BKN∗12a].

These experiments suggested the possibility of our shape display system. However, this system has some limitations. One of the main limitations is that this system adapts the manner of touching only for a single finger, not for two or more fingers as used in pinching, grasping, and so on. With visual displacement of a user’s hand alone, we cannot adapt to the situation in which there are two or more contact points between an object and a hand. To realize the proposed system, we must realize a means not only for displaying various complicated shapes but also for adapting to various ways of touching such as those shown in Figure 3.

In this paper, to solve this problem, we propose a method of modifying an identified size of objects not only by displacing the visual representation of the user’s hand but also by deforming it as if the user were handling the virtual shape. This method gives the users the impression that they are handling the virtual shape, although in actuality they are handling another shape.

We construct an algorithm to generate the visual feedback necessary to provoke the pseudo-haptic effect. We then use this algorithm to examine the possibility of exploiting the pseudo-haptic effect to modify an identified-size object handled with two fingers, and thereby confirm the availability of this algorithm for our proposed shape display system.

2. Related Work

While much research has been conducted on cross-modal effects between our haptic sense and other senses, herein, we mainly focus on the effects between our haptic sense and vision, which we aim to use in our system.

Haptic illusion that combines a presentation of forces with a manipulation of visual stimuli has a long history, dating back to Charpentier’s size-weight illusion [MEBR99], which showed that subjects estimated the weights of objects of equal mass on the basis of their apparent sizes. His work revealed that subjects felt an object was lighter when it appeared larger in their vision.
Pseudo-haptics, which is one of the illusional phenomena triggered by this characteristic of our sense, was first presented by Lécuyer [Léc09]. Lécuyer et al. made subjects push their thumb against a piston which was in turn pushed against an isometric Spaceball device. Simultaneously, subjects were visually presented with the compression of a virtual spring. Even though the Spaceball was not compressed, the perception of stiffness was influenced by the virtual spring. We can easily attempt to reproduce this effect in PowerCursor [PC], a Flash toolkit used to create interfaces that a user can touch. This toolkit was developed by Mensvoort during his work on simulated haptic feedback [vM02]. Pusch et al. proposed a pseudo-haptic approach, called HEMP, hand-displacement-based pseudo-haptics, which provides haptic-like sensations by displacing a visual representation of the user’s hand [PMC09]. They showed that when a subject wearing a head-mounted video see-through display (HMD), placed a hand in the opening of a pipe, and the HMD presented a virtual image of the hand moving to the right, the subject felt a force on the hand even though no physical force was exerted.

In addition, some research results show the potential for pseudo-haptic effects on our perception of not only force but also texture [ISK∗08, LBT08] and shape. Research has shown that when we are presented with conflicting sensory stimuli, vision usually dominates our perception of shape. Gibson’s work [Gib33] is an example of this type of research, which showed that a subject moving his or her hand along a straight flat surface while wearing distorting glasses, feels the straight surface as if it were curved. We can also consider the work of Rock and Victor as another example [RV64]. They asked their subjects to hold an object with a cloth while viewing the same object through a distorting lens. In this experiment, subjects matched the shape of the test object to the shape most similar to the distorted visual image they saw, rather than to the shape they actually touched. Kohli et al. found that distorting the pointer showing the position of the device along a flat surface of the desk can change the perception of the shape of the surface [Koh09]. Their work revealed that when subjects traced the device on a flat surface with the visual presentation as if they were tracing it on a curved surface, they perceived the curved one in their vision.

Other research work has revealed that in some cases, even though visual stimuli are not given complete priority over haptic stimuli, cross-modal effects between these two sensations influence our perception to some extent. Nakahara et al. found that when users of a mixed-reality system are presented with haptic and visual cube-shaped objects having discrepant edge curvatures, they perceive the curvature as somewhere between those of the two objects [NKO07].

3. Modification of an Identified Size of Object Held with Two Fingers

To realize the modification of an identified size of object held with two fingers, we constructed a visuo-haptic system using the pseudo-haptic effect by deforming a visual representation of the user’s hand.

3.1. Visuo Haptic Video See-Through System

We constructed the simple video see-through system as shown in Figure 4. In this system, users are deceived that they are touching virtual objects whose shapes are different from the physical objects that they are actually touching. Users touch a physical object placed behind a visual monitor and view it through the 3D monitor.

We placed two web cameras at locations corresponding to a user’s eyes through a mirror, and we captured images around the user’s hand. In this geometry, the binocular parallax is achieved by setting the distance between the cameras to 65 mm. The users sat on a chair and we nudged their heads to the viewing position that we had established. Using
the images captured by the cameras, the system realizes a stereoscopic video see-through display (Figure 5).

Touching the physically static object, whose shape is defined as $S_{\text{physical}}$, serves as the haptic stimulus. Watching an image as if the user were touching another object, whose shape is defined as $S_{\text{visual}}$, serves as the visual stimulus. The shape of the object reported by the user as the one perceived as touching is defined as $S_{\text{perceived}}$. In this system, we aim to change $S_{\text{perceived}}$ by changing $S_{\text{visual}}$ to a variety of shapes and by provoking the pseudo-haptic effect, but without changing the $S_{\text{physical}}$ of the object.

Using the video see-through system we composed, we conducted an experiment on the effects of pseudo-haptics on our perception of size of objects handled with two fingers (Figure 6). To simplify measuring the differences among $S_{\text{physical}}$, $S_{\text{visual}}$ and $S_{\text{perceived}}$, we chose a disk as the shape of the objects that subjects touched in the experiment.

### 3.2. Algorithm for Composition of Visual Feedback

In this study, we constructed an algorithm to generate the visual feedback necessary to provoke the pseudo-haptic effect and enable users to perceive objects of various sizes with only a single object of fixed size.

According to the procedure described in the following sections (see Figure 7), an image ($I_{\text{vf}}$) for visual feedback is composed from the images ($I_{\text{c}}$) taken by the two cameras attached.

#### 3.2.1. Extraction of Object and User’s Hand from Captured Image (I in Figure 7)

First, we extracted the area of the object and the user’s hand from the captured image on the basis of color. We created a blue background with a chroma key, which simplified color extraction.

#### 3.2.2. Object Scaling (II in Figure 7)

We scaled the appearance of the object (up or down) while maintaining the centroid of its area. Here we defined the scale factor as $R$. In addition, we calculated the change of the object’s area.

#### 3.2.3. Hand Deformation (III in Figure 7)

We used a deformation algorithm based on the position of control points on the hand [STJ06]. Using this algorithm, we deformed the shape of the hand easily and naturally using three control points. We defined the points where the user’s fingers contacted the object as contact points. The two points of contact between the object and hand, along with the centroid of the hand, are referred to as the control points. Below we describe the algorithm generated to deform the shape of the hand naturally for this particular grip.

We mainly focus on the situation where the user holds the object with a thumb and other finger(s); this can be seen in the upper image of Figure 7. The system uses the two contact points between the object and hand (one is on the thumb and the other is on the index finger) and the centroid of the user’s hand as the control points. Before we calculated the hand deformation, we detected the user’s two fingers with which s/he held the object and the position where his/her fingers contacted the object.

The first contact point was detected as the point of the user’s hand nearest to the centroid of the detected object area ($O_{\text{object}}$). This contact point is denoted by $F_1$.

The second contact point was detected as the point nearest to $O_{\text{object}}$ in the portion of the user’s hand excluding the
vicinity of F₁. This contact point is denoted by F₂. We defined an expected sector in terms of its center, which is the line F₁O_object, and its central angle, which is ± 80°. This sector is shown as the meshed area on the right in Figure 8. The detected contact points (F₁, F₂), and the centroid of the user’s hand (O_hand), are used as the control points before deformation.

Figure 9 shows how we deformed the shape of the user’s hand. During the deformation process, we replaced F₁ and F₂ with F₁′ and F₂′ where the user’s fingers contacted the virtually scaled object according to the change in the area of the object, as calculated in Section 3.2.2. In other words, we enlarged or shrunk F₁O_object and F₂O_object by a factor R, as described in the following expression for determining the coordinates of F₁′ and F₂′.

\[
F₁O_{object} : F₁′O_{object} = F₂O_{object} : F₂′O_{object} = 1 : R
\]

We then used these two replacement control points (F₁′, F₂′) and the centroid of the user’s hand (O_hand) as the updated control points. Based on the algorithm described by Schaefer et al. [STJ06], we deformed hand to move from F₁, F₂, and O_hand to F₁′, F₂′, and O_hand. While above-mentioned figures show the situation when a user’s thumb is detected first, this algorithm works well even if a user’s index finger is detected first.

3.2.4. Image Composition (IV in Figure 7)

Finally, we overlaid the images of the scaled object and deformed hand over the background image that we had prepared in advance. This is used for visual feedback. Furthermore, this method tolerates other grip types. Figure 10 shows the result of image processing for scaling an object held by hand.

4. Measurement of the Ability of Modifying an Identified Size of Objects

4.1. Purpose of the Experiment

We investigated the ability of our shape-display system based on the pseudo-haptic effect to control the perception of size of an object handled with two fingers. We conducted an experiment to examine how the effect of S_visual changed to S_perceived, and compared these three shapes. If S_perceived resembled S_visual rather than S_physical, then we concluded that the visuo-haptic interaction was effectively provoked, meaning that the system worked as designed. Conversely, if S_perceived resembled S_physical rather than S_visual, then we concluded that the haptic stimulus was more influential for the perceived shape rather than the visual one. Thus, when the latter result was obtained, it indicated that it was difficult for our system to modify an identified a size of an object handled with two fingers, a thumb and other finger(s).

Hereinafter, we refer to the diameters of these three shapes as D_physical, D_visual and D_perceived.
The diameter of these disks was the same as the pre-
the sizes of objects that they handled behind the monitor.
Subjects a captured image on the monitor, and they reported
a subject handled an object with two
experiment to measure the ability to perceive the size when
Before we performed the experiment, we conducted a pre-
choosing from so-called answer disks
Figure 11: Subjects matched the size of a handled object by

4.2. Pre-Experiment

Before we performed the experiment, we conducted a pre-
experiment to measure the ability to perceive the size when
a subject handled an object with two fingers. We showed
subjects a captured image on the monitor, and they reported
the sizes of objects that they handled behind the monitor. Thus, in this pre-experiment, $S_{\text{physical}}$ and $S_{\text{visual}}$ were the same size.

The subjects reported the size of a handled object by
choosing the disk that they felt was the nearest in size from
among the disks of various sizes. The diameters of these
disks ranged from 5 mm to 110 mm with a step of 5 mm
(Figure 11). Each subject chose one of these disks and then
handled it with the same hand as for $S_{\text{physical}}$ to compare the
sizes of this disk and $S_{\text{physical}}$. Repeating this trial, the sub-
jects chose the disk that they felt matched the disk behind
the monitor. We call these disks the answer disks.

We chose disks of three sizes as $S_{\text{physical}}$. The diameter
of these disks was 30 mm, 55 mm, and 80 mm. Five men
in their twenties participated in this pre-experiment and four
trials were conducted for each $S_{\text{physical}}$.

Table 1 shows the result of this pre-experiment. These re-
results show that the size of $S_{\text{perceived}}$ was almost the same as
the size of $S_{\text{physical}}$ and $S_{\text{visual}}$. This proves that the video
see-through system functioned successfully for the perception
of size. Throughout all trials, the difference in size be-
tween $S_{\text{physical}}$ and $S_{\text{perceived}}$ was within ± 5 mm, so the
perception error for the sizes of the objects was within that
range. Using this result, we conducted the experiment to in-
vestigated the ability of our shape-display system based on
the pseudo-haptic effect to control the perception of size of
an object handled with two fingers.

4.3. Experiment

In this experiment we chose disks of three sizes as $S_{\text{physical}}$.
The diameter of these disks was the same of the pre-
experiment, 30 mm, 55 mm, and 80 mm. For each size
of $S_{\text{physical}}$, the subjects were shown disks whose diameter are
from ($D_{\text{physical}}$ - 30) mm to ($D_{\text{physical}}$ + 30) mm every
10 mm as $S_{\text{visual}}$. This interval of the diameter of $S_{\text{visual}}$ was
determined by the ability of the perception of size we esti-
Jated from the result of the pre-experiment. Nine men and a
woman in their twenties participated in this experiment, and
two trials were conducted for each combination of $S_{\text{physical}}$
and $S_{\text{visual}}$. These combinations were presented to subjects
in a random order.

We set no time limit for the subjects to answer what size
they felt, but we gave them the following five instructions.

- Subjects must watch the image presented on the monitor
  when touching the object.
- Subjects must touch the object with a thumb and other
  finger(s).
- Subjects must handle the mid line of the object.
- Subjects must touch $S_{\text{physical}}$ and “the answer disks” with
  their same hand.
- Subjects may touch $S_{\text{physical}}$ and “the answer disks” re-
  peatedly.

We did not restrain the heads of the subjects with any equip-
ment. Instead, we instructed them not to move their heads
from the position that we initially set in realizing the video
see-through system. We measured the position of the heads
of the subjects, and confirmed that the subjects watched the
correct video see-through image on the monitor.

During the experiment, the subjects were not aware that
they actually touched only one kind of $S_{\text{physical}}$. In each trial
the experimenter only went through the motions of chang-
ing $S_{\text{physical}}$. In addition, the experimenter did not indicate
whether the hand position in the monitor was actually dis-
torted or not, and thus the subjects did not know whether
$S_{\text{visual}}$ was the same as $S_{\text{physical}}$.

As in the pre-experiment, the subjects reported the size of
a handled object by choosing the disk that they felt was the
nearest in size from among the disks of various sizes.

4.4. Results and Discussion

As our experimental result, we present the diameter of
$S_{\text{perceived}}$. Figure 12 shows the $D_{\text{perceived}}$ when 30 mm, 55
mm and 80 mm diameter disks were presented as $S_{\text{physical}}$.
Two observations are common to these three results. The
first is that $D_{\text{perceived}}$ is almost same as $D_{\text{virtual}}$ when $D_{\text{virtual}}$

<table>
<thead>
<tr>
<th>$D_{\text{physical}}$ (mm)</th>
<th>Means (mm)</th>
<th>SDs</th>
<th>Rate (%) of $D_{\text{physical}} - D_{\text{perceived}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.00</td>
<td>28.75</td>
<td>1.09</td>
<td>5</td>
</tr>
<tr>
<td>55.00</td>
<td>54.75</td>
<td>1.92</td>
<td>15</td>
</tr>
<tr>
<td>80.00</td>
<td>80.25</td>
<td>1.92</td>
<td>15</td>
</tr>
</tbody>
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Table 1: Sizes of objects that subjects felt handling

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is less than $\pm 10$ mm compared with $D_{\text{physical}}$. This suggests that our proposed method, deforming the visual representation of user’s hand can modify the perception of size of object handled with two fingers if the difference of size between visual and haptic stimuli is within $\pm 10$ mm, regardless of the size of the object that the subjects actually touch. The second observation is that $D_{\text{perceived}}$ differs widely from $D_{\text{visual}}$ when $D_{\text{visual}}$ is outside $\pm 30$ mm compared to $D_{\text{physical}}$. This indicates that it is difficult to modify the perception of size if the difference between the diameters visual and haptic stimuli is greater than 30 mm. By comparing the results of Figures 12(a) and 12(c), it can be seen that the difference between $D_{\text{visual}}$ and $D_{\text{perceived}}$ is greater when $S_{\text{physical}}$ is a 30-mm disk than when $S_{\text{physical}}$ is an 80-mm disk. The cause of this difference is apparently the difference in the ratio between $D_{\text{physical}}$ and $D_{\text{visual}}$. The perception of size is influenced by not only the absolute size difference but also the size ratio.

We arrange the results according to the size ratio between $S_{\text{physical}}$ and $S_{\text{visual}}$. Figure 13 shows that there is almost no difference between $D_{\text{visual}}$ and $D_{\text{perceived}}$ if the ratio between $D_{\text{physical}}$ and $D_{\text{visual}}$ is within the range from 0.6 to 1.35. Conversely, the difference between $D_{\text{visual}}$ and $D_{\text{perceived}}$ becomes large when the ratio of $D_{\text{physical}}$ to $D_{\text{visual}}$ is less than -50% or greater than 50%. This result indicates that we can modify an identified size of object if the ratio between visual and haptic stimuli is within the range from -40% to 35%.

5. Conclusion and Future Work

This paper evaluates the effectiveness of using a visuo-haptic shape display system for modifying an identified size of object handled with a thumb and other finger(s). This system uses a pseudo-haptic effect based on the visual deformation of a user’s hand touching an object.

To realize the proposed system, we must realize a means for not only displaying various complicated shapes but also adapting to various ways of touching such as pinching and
grasping. Thus, we need to not only displace the visual representation of the user’s hand but also to deform it. In this study, we focused on modifying an identified size of an object handled with a thumb and a other finger.

We constructed an algorithm to generate the visual feedback necessary to provoke the pseudo-haptic effect by deforming the visual representation of the user’s hand as if the user were handling the virtual shape. We conducted an experiment to evaluate the effectiveness of the proposed algorithm, and a large portion of the subjects felt that they were not handling an object the size of the haptic stimulus, but rather an object of the size visually presented. This experiment proved that our algorithm can modify the perceived size of an object if the difference in size between the visual and haptic stimuli is within the range from −40% to 35%.

Thus, we conclude that it is possible to modify an identified size of an object by using visual feedback, and so this algorithm can be applied to the visuo-haptic shape display system we proposed. To derive more detailed specifications for the system, we should examine whether it is possible to modify the identified position and shape using this algorithm. Based on these measurements, we should have the proposed system adapt to various ways of touching. Then, we should decide on the range and accuracy of shapes to generate with physical devices. Finally, we can design the physical devices and visual display to generate the visual feedback and thus construct a system that provides users with the sense of freely touching a variety of shapes.

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References


