Touch & Detach: Ungrouping and Observation Methods for Complex Virtual Objects Using an Elastic Metaphor

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Abstract

In this study, we implemented a stable and intuitive detach method named "Touch & Detach" for 3D complex virtual objects. In typical modeling software, parts of a complex 3D object are grouped for efficient operation, and ungrouped for observing or manipulating a part in detail. Our method uses elastic metaphors to prevent incorrect operations and to improve the operational feel and responsiveness. In addition, our method can represent the connection and its strength between the parts by simulating a virtual elastic band connecting the parts. It helps users to understand the relationship between the parts of a complex virtual object. This paper presents the details of our proposed method and user study.

Keywords: Virtual Reality, Augmented Reality, Mixed Reality, Ungrouping and observation, Gesture, Audio-visual feedback, Elastic, Manipulation.

Index Terms: H5.2 [Information interfaces and presentation]: User Interfaces - Auditory (non-speech) feedback, Interaction styles, Input devices and strategies; H5.1 [Information interfaces and presentation]: Multimedia Information Systems - Artificial, augmented, and virtual realities.

1 Introduction

Technology enables users to manipulate complex, multi-part 3D virtual objects such as industrial products, structures designed by CAD, and models of the human body in large 3D space [1]. One of the applications is its use in training and education, such as for learning the structure of human body or industrial products.

In typical modeling software, parts of such a complex 3D object are grouped and manipulated together, but not individually, for efficient operation. Therefore, an ungrouping operation is necessary when the user wants to pick up only one part of a complex object to observe it in detail from various directions or to manipulate it.

In this study, we focus on a system with which users can ungroup a part of 3D virtual objects that are grouped, manipulate them, and observe them in 3D space. Our contribution is to propose "Touch & Detach"; the method installing "elastic metaphor" in real life for this ungrouping process (Figure 1).

In the circumstances which we focus on, users tend to make unexpected movements and accidentally detach a group of parts while rotating or moving an object. Our method can avoid such problem by implementing the condition that we ungroup parts of an object (defined as "detachment condition") on the basis of a real world metaphor, "elastic." The user can separate a group of objects according to the detachment condition, which helps users avoid incorrect operations. In addition, our method provides the users with audio-visual feedback based on the metaphor, and it improves the operational feel.

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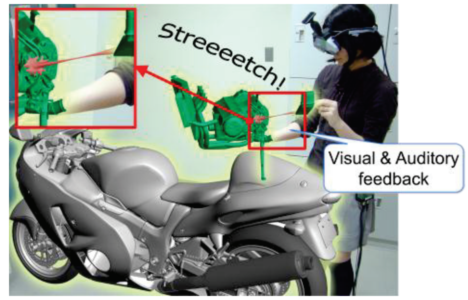


Figure 1: Concept sketch of "Touch & Detach." User can pick up a group of parts of the 3D virtual objects that they need and observe it.

2 Related work

2.1 Selection and manipulation

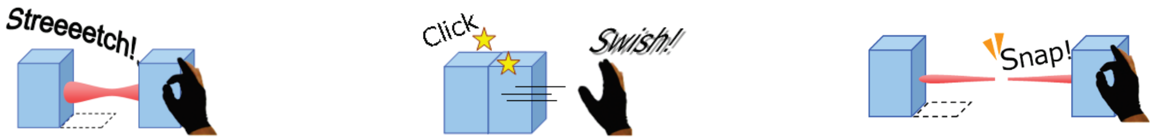
Several studies have examined various selection techniques because manipulating virtual objects is a fundamental operation [2]: single-object selection, multiple object selection, and selection of a group.

Examples of basic single-object selection using virtual hands [3, 4] include Go-Go [3], with which the user moves a virtual hand to reach the target object, and Ray-casting, with which the user uses a virtual ray to point to the target object [5, 6].

Many techniques have been proposed to manipulate a complex virtual object when there are other virtual objects in the same 3D space, such as those allowing a user to select target objects that are occluded by other objects or select target objects without incorrect selection [7-13].

Regarding techniques that select multiple objects, in typical modeling software, users can select objects using a rectangle or lasso tool or using a combination of keys such as the shift or control key while clicking with the mouse. Some studies have proposed techniques that are similar to traditional selecting techniques for 2D applications, such as using a rectangle, circle or lasso tool [14, 15]. These techniques enable the user to select multiple 3D objects at once. Some studies allowed the user to select 3D virtual objects using 3D selection volume. For example, Schmidt *et al*. [16] used a frustum and Ohnishi *et al.* [17] and Haan *et al.* [18] used a cuboid. Another technique enables the user to select multiple objects in more detail. Stenholt *et al*. [19] proposed a technique using a type of magic wand that selects a group of parts on the basis of their similarity and the distance between the objects.

In these methods, the users select multiple objects and manipulate them *in situ*. In contrast, in some proposed methods, multiple objects are grouped in advance. For example, in a typical modeling software, when the user performs complex 3D modeling, grouping multiple objects is natural. In a typical VR environment, the scene graph is used for the management of virtual objects. Similarly, some modeling software have similar functions such as the outliner/hypergraph in Autodesk Maya, the schematic view in Autodesk 3dsMax, and the scene editor in NewTek, Inc., Lightwave. In most cases, the user can select and manipulate



(a) Connection is displayed and auditory feedback is provided when the user moves a part from its initial position.

(b) When the user releases the part in the effective area, a wind sound is provided, and when it returns to the initial position, a clicking sound is provided.

(c) Connection is cut when the user moves the part outside of the effective area, and a snapping sound is provided.

Figure 2: Audio-visual feedback of virtual elastic band.

groups of objects via another window that shows a scene graph. These are indirect manipulation. A few studies consider the grouping and ungrouping methods and focus on direct manipulation. The method proposed by Onishi *et al.* [20] allows users to modify the branches and foliage of virtual tree models in which parts are managed by a hierarchy using an interactive bi-manual operation. However, the method is used only for a virtual tree model. The method proposed by Jang *et al*. [21] also manages objects using a hierarchy and allows users to select multiple parts at once. However, their method targets only the repeatedly aligned virtual objects that have a similar shape; it is not suitable for complex objects on which we focus.

In our study, we consider a method with which the user can manipulate a group of objects by directly touching the parts. Although many selection methods have been proposed, sometimes users select wrong parts and incorrectly ungroup. Therefore, to avoid such incorrect operations, we implemented an intermediate “detachment condition” based on the elastic metaphor, which allows the user to confirm whether the parts have been selected correctly during ungrouping.

2.2 Observation

Techniques have been proposed to observe complex objects that display the inner parts [22, 23] or separate the outer parts automatically depending on the position of the cursor [24]. These methods focus on the removed or separated outer parts and on the observation of occluded inner parts; they do not consider manipulating the removed or separated outer parts. In contrast, in our system, the user can detach one group of parts of a complex object and observe it while moving or rotating the object.

In addition, the connections and strength between parts are not considered in these techniques. We believe that the connection and connection strength between parts is important when observing and separating the varied structures of complex objects, in which the size and shape of parts may vary significantly Therefore, in our research, the connections are visualized using virtual elastic band.

2.3 Physical behavior

Many studies apply the metaphor of physical behavior in the real world to the virtual world. For example, rope metaphor was installed for navigation task [25], and rubber-band metaphor was also applied [26] for reducing the distance between the real and virtual hands. For the object manipulation, gravity and collisions [27-29] or magnetic force [30] were applied to the manipulation of virtual objects in virtual reality space. Recently, pseudo-physics for interacting with virtual objects in a tabletop system [31], or with virtual car interior in VR space [32] were proposed. Use of a physical behavior makes the manipulation of virtual objects more natural and comfortable. We applied such a physical behavior to the detaching operation of virtual objects. We expect our method to result in comfortable object manipulation and improve responsiveness.

The methods proposed in some studies [27, 28] are used to select single objects, not multiple objects; the method proposed by Goesele [29] does not allow the user to move the object after he/she has placed it. In addition, although the constraint between each object was considered, that between a single object and multiple objects was not considered. Consequently, these methods were not used for complex objects, such as target parts in contact with multiple parts.

Kitamura *et al*. [30] were able to place virtual objects easier using a magnet metaphor by constraining between the face-to-face surfaces of parts and reducing the degree of freedom of object movement. Although the purpose of their model using a magnet metaphor was to easily place virtual objects, the surfaces were constrained to each other even if they were not in contact. By installing this model, the user can confirm the above described situation, i.e., “whether the selected parts are correct” while detaching, and avoid incorrect ungrouping.

However, when using the magnet metaphor, the users do not know how far they have to move the parts to ungroup it because they cannot estimate the magnetic force itself. Therefore, our method with an elastic metaphor will be more useful for avoiding incorrect ungrouping and will improve the operational feel by providing rich audio-visual feedback.

In this study, we confirmed these ideas through a user study that compared our elastic metaphor with conditions using the magnet metaphor and not using the any metaphor.

3 Proposed Method: Elastic Metaphor

We installed an elastic metaphor to detach parts and used a model in which each surface is connected by a “virtual elastic band.” First, to avoid users to accidentally detach, we set the detachment condition based on this metaphor. That is performed by selecting and moving a part out of the effective area, in other words, pulling it apart in order to break the elastic connection.

The size of the effective area d_{ela} is given by Equation (1) using the elastic strength k_{str}, the size of the bonding surface A_{ela}.

$$d_{ela}(A_{ela}) = k_{str} A_{ela} \tag{1}$$

If the part is in the effective area ($|\mathbf{p}_{p1} - \mathbf{p}_{p2}| \le d_{ela}$), when the user releases it, it is drawn by the elastic force and returns to the initial position. Where $\mathbf{p}_{p1}$ is the 3D position of the center of the constraint surface selected by the user and $\mathbf{p}_{p2}$ is that of the paired surface. If the part is moved out of the effective area ($|\mathbf{p}_{p1} - \mathbf{p}_{p2}| > d_{ela}$), the ungrouping is complete.

In addition, the user can check the current conditions, and the operational feel is improved with audio-visual feedback while detaching.

When the user detaches a group of parts, the elastic band that connects each surface of the parts expands and contracts depending on the distance between the parts; simultaneously, its width also changes (Figure 2a). When the user releases the part in the effective area, it returns to its initial position (Figure 2b).

As it was mentioned in Section 2, we applied a physical behavior to the detaching operation of virtual objects in order to increase the operational feel. We designed the elastic force between the parts, F_{ela}, to be proportional to k_{str}, A_{ela}, and the distance between the parts (as shown by Equation 2 and Figure 3):

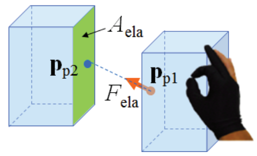


Figure 3: The elastic force between parts F_{ela}.

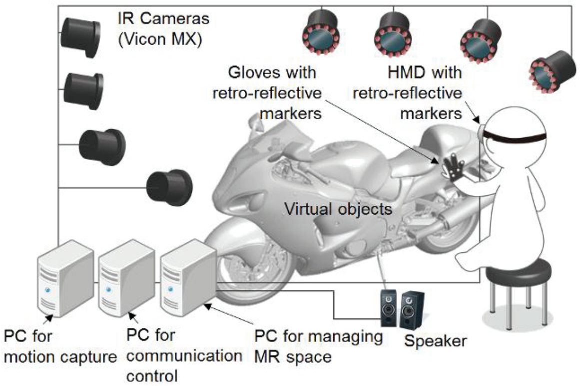
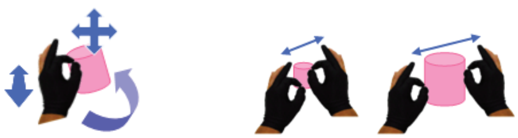


Figure 4: System configuration.



(a) Moving and rotating (b) Scaling

Figure 5: Gesture operations.

$$F_{ela}\,(A_{ela},\,\mathbf{p}_{p1},\,\mathbf{p}_{p2}) = k_{str}\,A_{ela}\,\left|\mathbf{p}_{p1}-\mathbf{p}_{p2}\right| \qquad (2)$$

When the user moves a part toward the limits of the effective area, the elastic becomes thin, and finally it breaks, canceling the elastic force (Figure 2c).

Our system also provides auditory feedback in the situation when the user pulls the elastic, releases a part, the part returns to the initial position, and the elastic breaks.

4 Implementation

4.1 System configuration

We developed a mixed reality (MR) system with gesture operation (Figure 4) that uses the proposed methods. Users view the MR space through a video-see-through head-mounted display (HMD, Canon VH-2002). To generate the MR space, two real-world input images are captured from the HMD cameras through a video capture card (ViewCast Osprey-440) on the PC for managing MR space (Windows7 OS, Intel Core i7 965 EE 3.20GHz CPU, 6G RAM). Next, the images are generated in real time using the HMD's position and orientation. The images are superimposed onto the real-world images. Then, the two output images from a graphics card (NVIDIA Quadro FX 1700) are displayed to the user by each HMD display.

Hand gestures are detected by a ViconPeaks motion capture system. It uses infrared technology to enable tracking of finger positions and the position and orientation of the HMD. Auditory feedback is presented through a speaker.

4.2 Gesture Operation

4.2.1 Ungrouping & observing

In our system, the user can ungroup the target part or group of parts using his/her right hand (this setting can be altered as per the user's preference) along the way of Figure 2. After ungrouping, to observe the detached parts in detail, the user can move and rotate them by the left hand, and scale them by both hands (Figure 5).

4.2.2 Reconnect

In our system, we also implemented the reconnect function for the situation when the user wants to place the ungrouped parts (or group of parts) to the initial position and observe other parts. Using this function, the user can return the parts to the initial position in any order he/she chooses.

The reconnect function was implemented on the basis of the magnetic model of Kitamura *et al.* [30], in which magnets were placed on the surface of each part and connected to each other. Similar to a real magnet, when the user moves the selected parts to the corresponding parts and releases them, if the distance between them is shorter than the set threshold, they return to their initial positions.

The threshold d_{mag} (the size of magnetic force's effective area) is given by the following equation (k_{thr} is a coefficient, and A_{mag} is the size of the overlapping area of two magnetic surfaces) using Kitamura's method [30]:

$$d_{mag}\,(A_{mag}) = k_{thr}\sqrt{A_{mag}} \qquad (3)$$

If the part is in the effective area ($\left|\mathbf{p}_{p1}-\mathbf{p}_{p2}\right| \le d_{mag}$), when the user releases it, it returns to the initial position.

The visual feedback is provided to show where the selected parts will return to (Figure 6).

4.3 Results

Figures 7 show examples of a user detaching parts of a foot-bone model using the elastic metaphor.

5 User Study

5.1 Objective

To avoid incorrect operations and improve operational feel, our method uses the detachment condition for completing ungrouping and provides the audio-visual feedbacks on the basis of elastic metaphors: In user studies, we evaluated the following two benefits of our technique by comparing it with the condition without a metaphor:

(1) The benefit of a detachment condition that uses the elastic metaphor to avoid incorrect operations.

(2) The benefit of the audio-visual feedback that uses the elastic metaphor for increasing the operational feel.

In addition, we also compared our technique that uses an elastic metaphor with the detachment conditions that use a magnet metaphor and confirmed the difference.

5.2 Preparation

5.2.1 Implementation of undo function

As previously mentioned in this user study, we compared our technique with those without a metaphor. Our approach of "avoiding incorrect operation using detachment condition based on the metaphor" avoided incorrect operation in advance.

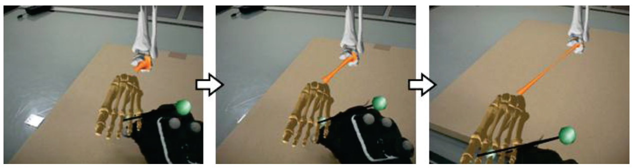
In contrast, many types of software include an undo function that allows the user to cancel an operation and retry it again afterward. Therefore, we implemented an undo function for incorrect ungrouping and compared it to our method. When the user presses the undo key, the parts return to the initial position.

5.2.2 Implementation of magnet metaphor

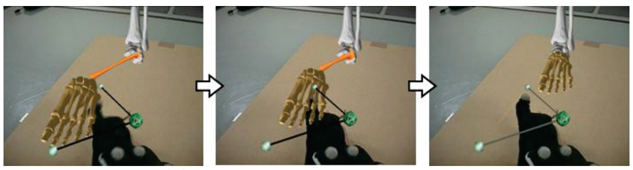
We also applied a magnet metaphor, proposed by Kitamura et al. [27] for manipulating virtual objects, to our system in order to compare it to our proposed method that use an elastic metaphor.

(a) Out of the effective area: half-transparent (b) In the effective area: Opaque

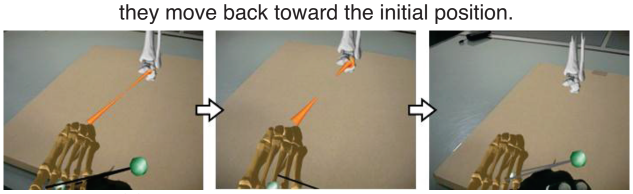
Figure 7: Visual feedbacks of reconnect. After the ungrouping, when the user picks up the parts, the color of the magnet surfaces of the selected parts and the corresponding parts will change.



(a) The user selects and pulls the parts.



(b) After the user releases them, they move back toward the initial position.



(c) The elastic breaks when the user pulls the parts out of the effective area.

Figure 8: Elastic metaphor.

Similar to the way we implemented the reconnection function in Section 4.3, we used the model in which magnets are placed on the surface of each part and connected to each other. As visual feedback, semi-transparent red and blue boards appear as virtual magnets. Based on this model, we set the separating condition following.

If a part is in the effective area of another part's magnetic force, the forces interact. When the user releases the part, it returns to its initial position (Figure 8a). Conversely, when a part is out of the effective area, it remains at the position where the user released it and the ungrouping is complete (Figure 8c).

In the case of the magnet metaphor, the detachment condition is performed by selecting and moving the parts out of the effective area (under the effect of magnetic force), and later releasing them. The size of the effective area of the magnetic force d_{mag} is also given by the Equation 3 in Section 4.2.

When the user releases the part in this area, it returns to its initial position by the attractive force F_{attr} from the other part's magnetic force. At the moment when the part returns, the system provides a clicking sound as auditory feedback (Figure 8a). F_{attr} is proportional to A_{mag} and inversely proportional to the square of the distance between the parts (Equation 4).

$$F_{\mathrm{attr}}(A_{\mathrm{mag}}, \mathbf{p}_{\mathrm{p1}}, \mathbf{p}_{\mathrm{p2}}) = k_{\mathrm{attr}} \frac{A_{\mathrm{mag}}}{|\mathbf{p}_{\mathrm{p1}} - \mathbf{p}_{\mathrm{p2}}|^2} \tag{4}$$

F_{attr} is given by using these parameters and the constant k_{attr} (Figure 8b).

5.3 Participants

In this user study, 18 students were used as the subjects (15 males and three females in their 20s). None of the students had experience of using our system.

5.4 Experimental design and procedure

We compared the number of errors and the operational feel using five conditions as follows:

(a) With the detachment condition that used an elastic metaphor, with audio-visual feedback (the virtual elastic band and its sounds).

(b) With the detachment condition that used an elastic metaphor, but without audio-visual feedback.

(c) With the detachment condition that used a magnet metaphor, with audio-visual feedback (the clicking sound when the part returns to its initial position and visual feedback is semi-transparent red and blue boards as magnet surface).

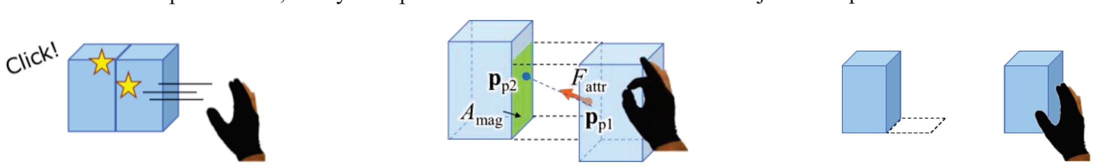
(d) With the detachment condition that used a magnet metaphor, but without audio-visual feedback.

(e) With the detachment condition that use neither a metaphor nor audio-visual feedback.

To confirm the first benefit mentioned in Section 5.1, we tracked the number of incorrect operations and checked whether they are reduced by implementing the metaphors, compared the results using the conditions without a metaphor, and compared the differences between magnet and elastic metaphors.

The subjects were asked to ungroup the target part from the experimental model (Figure 9a) that was grouped in advance for the trial. The target part is shown by changing its color, and after the user ungrouped it correctly, the color turned to a default color and returned to its initial position. The targets were randomly chosen. If a subject ungrouped a part that was not the target part, it was counted as an error. The subject needed to undo the separation, and try again until he/she successfully ungrouped the correct part. In this user study, to make the all of conditions even, the subjects use only "undo," not "reconnect". Because there was a possibility that the user would not be aware of the error, the system provided a sound feedback for both correct and incorrect operations.

For one trial, the users needed to ungroup the part correctly. After each trial, the users were requested to return their hands to a position in front of their bodies on the desk. Each subject was asked to ungroup 10 parts using five different detachment conditions, three times for each part, which totaled 150 trials. We randomly changed the order of the conditions used by each subject and so that no other subject performed the trials in the same order. The subjects can practice the each condition using the



(a) When the user releases the part in the effective area, it returns to its initial position, and a clicking sound is provided. (b) The attractive force F_{attr}. (c) When the user releases the part outside the effective area, it stays where the user placed it. The ungroup is complete.

Figure 6: Magnet metaphor: The forces and behaviors when the user moves the part from the first position.

model for practice (Figure 9b) in advance, until they become accustomed to each condition.

The subjects were seated while performing these tasks. They were allowed to freely move their heads. The undo function was used by pressing a key near their left hand. The scene of this user study is shown in Figure 10.

To confirm the second benefit in Section 5.1, we evaluated the effectiveness of the audio-visual feedback based on the elastic metaphor and compared it with the feedback based on the magnet metaphor or conditions without the feedback from the perspective of increasing the operational feel.

After completion of the tasks, subjects evaluated the operational feel on a five-point scale from 1 to 5, where 5 was the highest. If required, they were allowed to freely ungroup the same experimental model for each condition.

We defined the operational feel as the following four factors.

Presence

"You can feel that the object exists in front of you, and you are able to ungroup it by picking and pulling it,"

Feeling of ease

"You can recognize the current condition, such as which part you selected, or ungrouping is complete or not"

Comfort

"You can feel whether the operation is comfort."

Ease of ungrouping

"You can easily ungroup."

We described these definitions to the subjects in advance.

In addition, subjects also evaluated the perceptual operational time by sorting from 1 to 5, where 5 is the slowest.

Subjects are allowed to comment freely during the experiments.

5.5 Results

5.5.1 Avoiding incorrect ungrouping

The boxplots of "number of errors" for each of the five conditions are shown in Figure 11. ANOVA showed a significant difference in error rate between the five conditions ($F = 24.55$, $p < 0.01$). A Tukey post-hoc analysis indicated that all tests using detachment conditions based on elastic and magnet metaphors (conditions a-d) resulted in a significant reduction of the number of errors when compared with the results from the tests that did not use a metaphor (condition e). On the other hand, there were no significant differences between the results from the tests using elastic and magnet metaphors (conditions a-d).

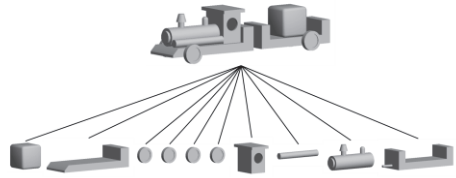
The results show that the number of errors decreased in tests where the detachment condition was considered in comparison with the tests where that it was not considered. The differences are clearly shown. Therefore, we confirmed that subjects can avoid to incorrect operations by the detachment condition based on each metaphor avoided unexpected operations.

5.5.2 Increasing operational feel

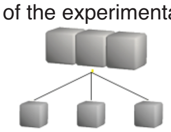
The boxplots of "operational feel" of the five cases are shown in Figure 12. Friedman Test showed a significant difference between the five conditions for all types of feeling. (In "presence" χ^2=27.86, "feeling of ease" χ^2=47.63, "comfort" χ^2=35.02, "ease of ungrouping", χ^2=36.59, df=4, N=18, $p < 0.01$, in all factors).

Regarding the elastic metaphor, a Steel-Dwass post-hoc analysis indicated that the condition with audio-visual feedback based on the elastic metaphor (condition a) was ranked significantly higher ($p < 0.01$) than all other conditions without the feedback (conditions c-e) for all types of feeling: presence, feeling of ease, comfort, and the ease of ungrouping.

From these results, we observed that the audio-visual feedback based on the elastic metaphor that we proposed increases the operational feel significantly.



(a) Tree structure of the experimental model (toy train).



(b) Tree structure of the practice model.

Figure 9: Models for user study.

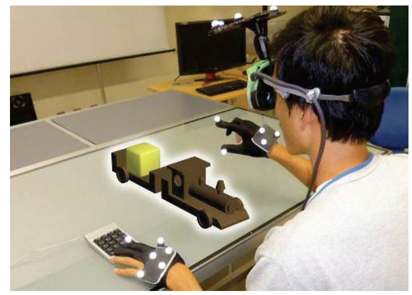


Figure 10: Scene of user study.

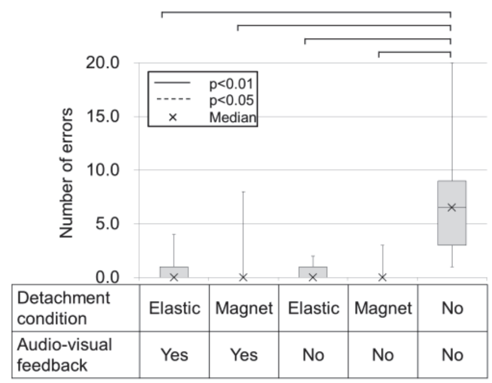


Figure 11: Result of "Number of errors"

Regarding the magnet metaphor, the condition with feedback based on the magnet metaphor (condition b) was ranked significantly higher ($p < 0.05$) than the conditions without a metaphor (conditions e) for three types of feeling: feeling of ease, comfort, and ease of ungrouping.

In addition, most of the subjects reported that in the case with the audio-visual feedback, they could perform the task and understand the current situation easier than in the case without the feedback. In particular, they preferred the feedback based on the elastic metaphor because it clearly showed whether it was in the effective area, and when they released the parts before ungrouping, the parts returned quickly.

When there was no feedback, such as in the condition using a magnet metaphor, some subjects commented that they preferred the condition without a metaphor and with the undo function, because the task took more time when using a magnet metaphor.

On the other hand, in the case using an elastic metaphor, after the ungrouping was completed, the subjects could not return the parts (a reconnect function was needed) to the initial position using the metaphor. Therefore, the magnet metaphor is useful as a reconnect function in such a case.

Presence (Figure 12a)

As previously mentioned, the rate of condition with audio-visual feedback based on the elastic metaphor (condition a) was ranked significantly higher than all other conditions without the feedback (conditions c-e). The result indicated that the audio-visual feedback based on the elastic metaphor is an appropriate mental model. Furthermore, the audio-visual feedback achieves an increase in the presence.

On the other hand, one subject commented that he could not imagine the metaphor, either the elastic or magnet metaphor, for this toy train model because elastic and magnet connections are rarely used for such a toy train model.

From this comment, we determined that the presence is affected on the basis of the suitability of the audio-visual feedback.

Two subjects evaluated the condition with magnet feedback as low, because they could not feel the force feedback during ungrouping. On the other hand, in the case with elastic feedback, it presented a force-like feeling using the audio-visual feedback without actual force feedback.

In contrast, one subject felt strange because the elastic audio feedback did not change even when he released parts from various distances. Considering this effect, the presence will be increased.

Feeling of ease (Figure 12b)

On the basis of the subject's comments, we found that the elastic audio-visual feedback allows the subjects to easily estimate the timing of the ungrouping operation and thus increases the feeling of ease than the magnet.

One subject commented that if the color of the magnet surfaces were changed depending on the status, the feeling of ease would be improved, although it would be a tradeoff with the presence.

Another subject commented that from the view of the feeling of ease, he preferred a larger size for the effective area; however, from the view of the ease of ungrouping, the large effective area makes the operation cumbersome.

From these comments, two functions are necessary:

- Switching between the cases with elastic or magnet feedback, and without a metaphor,
- Adjusting the size of the effective area,

depending on the subject's purpose and preference during the operation.

Comfort (Figure 12c)

Similar to other assessment, the rate of condition with the audio-visual feedback was higher than that of without the audio-visual feedback.

On the other hand, one subject felt auditory feedback based on the elastic metaphor was cumbersome. Therefore, allowing subjects to turn the feedback on or off is necessary; otherwise, they can use the less auditory feedback case that uses a magnet metaphor.

Ease of ungrouping (Figure 12d)

Similar to other assessment, the rate of condition with the audio-visual feedback was higher than that of without the audio-visual feedback.

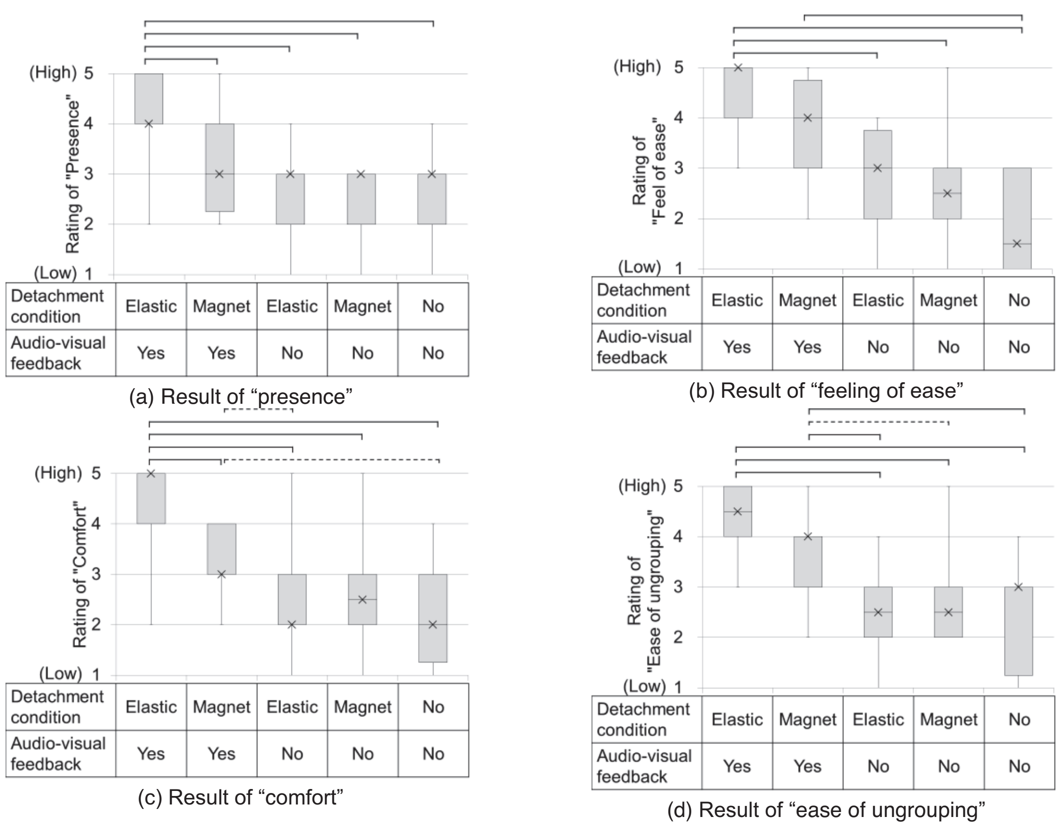
Another subject pointed out that when the effective area is not visualized, he preferred the case without a metaphor, because as soon as he selected the wrong parts, the system distinguished it as an error and he could execute the undo function.

Perceptual speed of operation

The boxplots of "operational time" and the "rating of perceptual speed of operation" are shown in Figures 13 and 14, respectively.

As shown in Figure 13, regarding the actual operational time, ANOVA showed a significant difference between the five conditions ($F = 7.998$, $p < 0.01$), and a Tukey post-hoc analysis indicated that the condition based on the magnet metaphor (conditions b and d) were significantly faster ($p < 0.05$) than the condition without a metaphor (condition e).

We assumed that in the condition with both detachment conditions and audio-visual feedback, the actual operational time would be longer than in the condition without a metaphor, because the users needed to move the parts out of the effective area and confirm the feedback. However, only the conditions using the magnet metaphor required significantly longer times



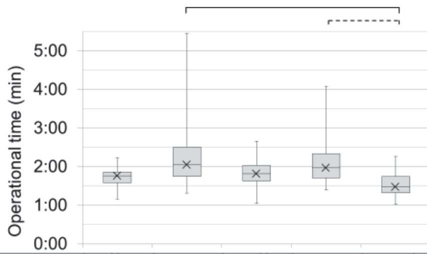
(a) Result of "presence"

(b) Result of "feeling of ease"

(c) Result of "comfort"

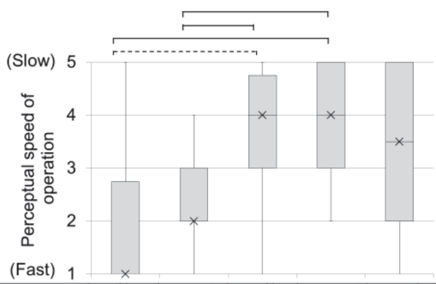
(d) Result of "ease of ungrouping"

Figure 12: Result of "Operational feel"



Detachment condition	Elastic	Magnet	Elastic	Magnet	No
Audio-visual feedback	Yes	Yes	No	No	No

Figure 13: Result of “operational time”



Detachment condition	Elastic	Magnet	Elastic	Magnet	No
Audio-visual feedback	Yes	Yes	No	No	No

Figure 14: Result of “perceptual speed of operation”.

Figure 15: Foot-bone model. Number of parts is 30.

than the condition without a metaphor.

In the case without a metaphor, although the users did not need to confirm the feedback, the error number was larger than for other conditions using metaphors. In the case using the elastic metaphor, the effective area is shown more clearly than for the case using the magnet metaphor; this reduces the number of errors in some subjects’ trials. For these reasons, there is a possibility that the difference was not significant between the operation times for the conditions using the magnet metaphor and without a metaphor.

Regarding perceptual speed of operation, we assumed that the perceptual speed of operation would be the same or faster than for the condition without a metaphor, because the user can avoid incorrect operations and the feedback increased the operational feel. As shown in Figure 14, regarding the perceptual operational speed, Friedman Test showed a significant difference between the five conditions (χ^2=19.69, df=4, N=18, $p < 0.01$), and a Steel-Dwass post-hoc analysis indicated in the conditions with audio-visual feedback (conditions a and c), subjects perceived significantly faster ($p < 0.05$) than in the conditions without feedback (conditions b and d). However, there was no significant difference between the conditions with and without a metaphor. Therefore, the implementation of at least the audio-visual feedback increased the perceptual speed, compared with the case by implementing only separation conditions.

Six of the 18 subjects commented that the perceptual speed was affected by the number of errors, and another six subjects commented that it was affected by the size of effective area. Regarding the number of errors, Figure 11 shows that in the case without a metaphor, the number is significantly larger. On the other hand, regarding the size of the effective area, the condition without the metaphor was shortest. Therefore, we believed there was no significant difference of the rate of perceptual speed between the condition with and without a metaphor.

One subject commented that the elastic audio feedback provided the pseudo-weight and made the reduced perceptual speed. From this comment, we determined that the audio feedback provides presence, but if it is excessive, it can possibly reduce the perceptual speed. For this issue, the subject can use the function of turning the audio feedback on or off, or use the condition that uses the magnet metaphor, which provides less auditory feedback.

6 Applying more complex object

We applied the proposed method using an elastic metaphor to a more complex model (Figure 15) and confirmed whether our method could be successfully used for a complex model through an informal user test.

For the test, we set the size of effective area using Equation 3, and we found that because the difference of the size of contact area between maximum and minimum is larger than the model used in the user study, the size of the effective area also becomes larger, making ungrouping difficult. Therefore, we corrected the size of the effective area using the following equation:

$$d'(d) = (d'_{\max} - d'_{\min}) \frac{d - d_{\min}}{d_{\max} - d_{\min}} + d'_{\min} \qquad (5)$$

$$(d_{\min} \leq d \leq d_{\max})$$

In this test, we decided through actual trial beforehand that the maximum and minimum sizes of the effective area are 420.0 mm and 126.0 mm, respectively (before correction, the maximum and minimum sizes were 514.5 mm and 3.8 mm, respectively).

The subjects were 12 students from the previous user study. They were required to ungroup the object freely, comparing with the impression in the case using the user study's model (Figure 9a) and commenting freely. For this comparison, we used the students who have experienced our system as subjects. Of the 12 subjects, 11 commented that when the model was complex, they preferred the case using an elastic metaphor over the case that did not use a metaphor.

The reasons were as follows:

- In the case without a metaphor, because they could detach the parts easily, the subjects could not get a feeling of ease and presence. Especially, when the model was complex, the feeling appeared remarkably. Although the complexity of the model increased the chances of making an incorrect selection, with the elastic metaphor, the subjects could avoid incorrect ungrouping.
- In the case using an elastic metaphor, even when the model was complex, the subjects easily understood the initial position and grouping of objects owing to the virtual elastic band feedback.
- In the case where the parts were grouped, when using the elastic metaphor, the subjects could understand the group structure by pulling the parts apart before ungrouping.
- The elastic metaphor was suitable for the foot-bone model. The metaphor is more suitable when subjects have to imagine organic objects using virtual objects.

However, the selection of small parts was still difficult. For this issue, there is a possibility to avoid errors in selection by using gestures such as moving, rotating, and scaling.

7 Conclusion and Future work

In this study, we proposed a method by which users can ungroup a complex virtual object in 3D space into small parts. This method avoided incorrect operations and improved operational feel by setting the detachment condition for separating the parts of an object and providing audio-visual feedback to users using the real-world metaphors; "elastic".

The result of our user study showed that the proposed method decreases the incorrect operations by the detachment condition on the basis of the elastic metaphors. Furthermore, our method increases the operational feel by using the rich audio-visual feedback. Even when working with a complex model, we were able to confirm that our method was effective. Based on this, there is the possibility that our elastic metaphor can apply to new ungrouping method with rich operational feel [32].

Although we realized this method in MR, of course it is possible to apply this method to operation in virtual reality and ordinal CAD system. .

In this study, we used virtual objects that were grouped in advance; however, some studies allowed users to group some parts dynamically. Sturzlinger *et al.* [34] proposed an automatic grouping method using the proximity of the parts in VR space. Oh *et al*. [35] also proposed a similar method using gravitational relationships in which the user can make groups and a hierarchy of the parts by piling them up. In future, we plan to implement functions similar to those used in these studies for grouping and dynamically making a hierarchy.

Regarding the user study, we need to run the quantitative evaluation in the case that the density and/or number of parts are increased. For the occlusion problem, we have to extend our method; such as the user can pull out multiple parts one by one, and pin them for observing the occluded parts.

We also plan to apply new metaphors and increase the number of choices available to the users, depending on their preference or task, to adjust the parameters of each metaphor's behavior via experience; and to analyze and consider the most suitable sound among the many sound effects available.

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