IEEE Virtual Reality, Houston, USA, March 13-17, 1999

Virtual Chopsticks: Object Manipulation using Multiple Exact Interactions

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Abstract

A technique is proposed for object manipulation with a virtual tool using multiple exact interactions. Exact test is introduced that uses real-time collision detection for both hand-and-tool and tool-and-object interactions. Chopsticks are adopted for one of the trials of our technique; although they have a very simple shape, they do have multiple functions. Here, a virtual object is manipulated by the virtual chopsticks, which are used by the motion of a user's hand captured by a hand gesture input device. Exact interaction is applied between the hand and chopsticks based on correct table manners. Experimental results demonstrate the effectiveness of the proposed multiple exact interactions, especially for precise object alignment tasks.

1. Introduction

Virtual reality (VR) techniques can be used to provide a sophisticated intuitive user interface using the experiences of humans and the capability of physical motion in a 3-D environment. For example, a glove-type device is often used to enable a user to manipulate virtual objects intuitively using a hand-grasping metaphor. With almost all previous VR systems, however, no more than simplified interactions between the hand and objects are considered, i.e., simple hand gestures and approximated object shapes are used to investigate interactions. A typical example is a user moving a representative point attached to his/her hand with a glove-type device into the bounding sphere or box of an object and having the object be recognized as grasped (or released) by the user by the closing (or opening) of the user's hand.

An approximated virtual object manipulation interface can be easily designed by using simplified interactions between a hand and objects, but this design would clearly lack reality and would make precise object manipulation difficult. For example, the precise alignment of virtual objects would be impossible to achieve if the user had to pay attention to the grasping position on the surface of the object. For this reason, it is necessary to introduce exact interactions between the hand and objects. Huang et al. proposeed an exact hand-grasping model using interactions between objects and spheres attached to the joints of fingers [1].

Humans often use "tools" to manipulate objects in a real environment. In order for humans to implement tools to manipulate objects in a virtual environment, it is necessary to consider multiple exact interactions, i.e., both the interactions between the tools and objects and the interactions between the hand and tools. If such multiple exact interactions were to be introduced for virtual object manipulation employing tools just like in a real environment, we could limit the operations and functions of the tools. Then, by utilizing these limitations, we could design an intuitive manipulation interface for virtual objects with a highly sophisticated mental model.

This paper proposes an object manipulation technique with a virtual tool using multiple exact interactions. Exact test is introduced for both hand-and-tool and tool-and-object interactions together with an elaborate hand shape model. Chopsticks are adopted as they are one of the tools we use in everyday life. Although they have a very simple shape, they do have multiple functions.

This paper first describes a classification for a virtual tool to manipulate objects. Then, descriptions are made on exact interactions between a hand and chopsticks based on correct table manners and exact interactions between tools and objects based on a real-time collision detection method. Next, experimental results are shown and demonstrate the effectiveness of the proposed multiple exact interactions, especially for precise object alignment tasks.

2. Classification of Object Manipulation Work using a Tool

This section discusses a classification of object manipulation work using a tool. Four types of manipulation work can be considered according to where the dividing line between virtual and real should be delineated as shown in Table 1. Figure 1 also shows the same four types of work, where virtual hand/tool/object are described with broken lines. Chopsticks are illustrated, but the tool is not limited to chopsticks.

In the real world, a real tool operated by a real hand manipulates a real object; i.e., the hand, tool, and object are all real in this case (type a). However, if only the object is virtual, the tool could manipulate the virtual object by having its motion captured by an adequate tracker. In this case, the hand and tool are real, but the object is virtual (type b), and therefore, focus is necessary on the interaction between the tool and object; it is not necessary to consider the interaction between the hand and tool. Type (c) is the case in which only the hand is real, while the tool and object are virtual. In this case, an adequate hand gesture input device could be used to capture the hand motion operating the virtual tool; therefore, consideration is necessary on both the hand-and-tool and tool-and-object interactions. Type (d) is the case in which the hand, tool, and object are all virtual. In this case, computer animation would to be generated for object manipulation using the tool by calculated constraints (e.g., inverse kinematics, dynamics or other deformation techniques) [2-5] instead of a motion capturing device.

In this paper, we discuss type (c) which requires careful consideration for multiple interactions between the hand and tool and tool and object.

Table 1: Classification of work using a tool

Type	**(a)**	**(b)**	**(c)**	**(d)**
Hand	real	real	real	virtual
Tool	real	real	virtual	virtual
Object	real	virtual	virtual	virtual

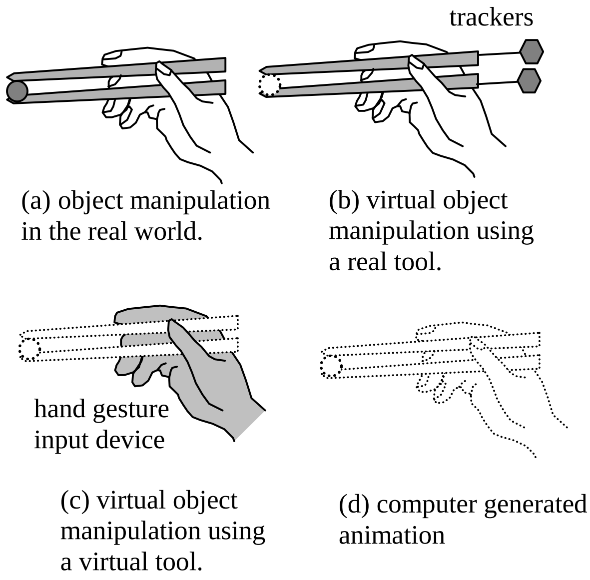

Figure 1: Four types of object manipulation work using a tool.

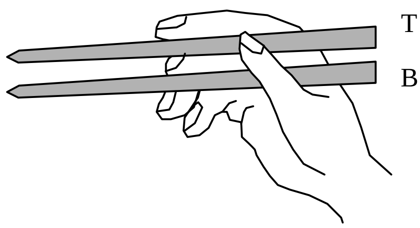

Figure 2: Proper chopsticks holding and handling.

3. Interactions between Hand and Tool

3.1. Chopsticks as a Tool

Chopsticks are one of the most popular tools in the world; more than 30% of all of the people on earth use them everyday [6, 7]. In spite of this popularity, people often feel difficulty when handling chopsticks. However, the most attractive features of chopsticks are their functions and shape; they constitute a single utensil with a simple shape, but they have multiple functions. Examples of such rich functions include grasping, picking up, supporting, carrying, cutting, tearing, flaking, peeling, scooping, wrapping, loading, pressing, pushing, splitting, piercing, and so on.

3.2. Proper Handling of Chopsticks

The exact interaction between a hand and chopsticks based on correct table manners described in [7, 8] is implemented. The proper holding method of chopsticks is described below (see Figure 2).

1. Bottom chopstick (B) is placed to the side of the nail of the ring finger, by putting it in the web of the right hand between the thumb and index finger.
2. Top chopstick (T) is placed to the side of the nail of the middle finger, by putting it in the web of the right hand between the thumb and index finger.

The proper handling method of chopsticks is described below.

1. Place the tips of the chopsticks neatly side by side. Move the top chopstick (T), while keeping the bottom chopstick (B) fixed.
2. Rotate the top chopstick (T) around the fulcrum sandwiched between the thumb and index finger by bending the index finger and middle finger so as to place the tips of the chopsticks neatly side by side.
3. Spread the tips of the chopsticks by stretching the index finger and middle finger.
4. Repeat 2 and 3.

Here, the top chopstick (T) is operated around the fulcrum sandwiched between the thumb and index finger, while a point on the nail of the middle finger is the point where force is applied. In addition, the bottom chopstick (B) is fixed between the root of the index finger and the thumb, and the points on the nail of and ring finger. The motion of the virtual chopsticks can be defined by imitating the correct use of chopsticks; i.e., establishing correspondences between points on the hand shape model and points on the chopsticks shape models.

3.3. Shape Models of Hand and Chopsticks

An elaborate hand shape model with 1,700 polygons (as shown in Figure 3) is used to introduce exact interactions between a hand and chopsticks. On the other hand, there are many kinds of chopsticks with different shapes in the world. We adopt hexagonal chopsticks as they are suitable in considering proper handling and are said to accelerate the intellectual growth of children [7]. Hexagonal chopsticks with 96 polygons for each chopsticks are shown in Figure 4. The length of a chopstick is determined to be 1.2 times the length of the hand shape (i.e., the length between the wrist and the tip of the middle finger) according to [7]; this is suitable for correct handling. Here, G is the representative point determined by dividing the chopstick axis internally 4:1, and chopstick direction vector v is a unit vector at the chopstick's axis that passes through G.

3.4. Chopsticks Handling Motion using Constraints

The motion of the virtual chopsticks is defined by establishing correspondences between points on the hand shape model and points on the chopsticks shape models derived from the correct handling method described above.

Constraints between the bottom chopstick and the hand are described first (see Figures 3 and 4). The point R, the vertex on the polygon of the root of the index finger, is defined as the fulcrum of the bottom chopstick, while the point S, the vertex on the nail of the rinng finger, is defined as the point where force is applied. The bottom chopstick is positioned so that vector v is aligned with vector RS, and G corresponds to R with the offset of the radius of the chopstick.

Similarly, the point P, the vertex on the polygon of the root of the index finger, is defined as the fulcrum of the top chopstick, while the point Q, the vertex on the nail of the ring finger, is defined as the point where force is applied. The top chopstick is positioned so that vector v is aligned with vector PQ, and G corresponds to Q with the offset of the radius of the chopstick.

If the hand shape model is deformed according to the manipulation of the hand gesture input device, both chopsticks are aligned with transformed vectors PQ and RS, respectively.

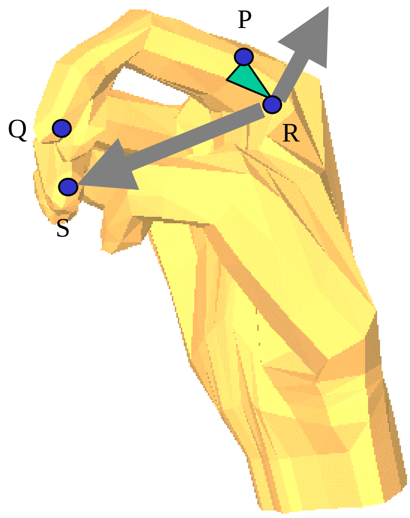

Figure 3: A hand shape model with 1,700 polygons.

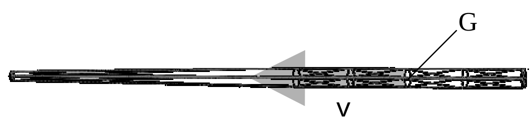

Figure 4: A hexagonal chopstick with 96 polygons.

3.5. Collision Avoidance

A finger may accidentally collide and interfere with other fingers because of the difference between the modeled hand shape and the actual user's hand wearing a glove-type device. The measurement errors of the device are sometimes the cause of the collision. In addition, collision and interference may occur between a finger and a chopstick or between a pair of chopsticks without any collision avoidance strategy. Therefore, we introduce a means of real-time exact collision detection and avoidance between chopsticks and between the middle finger and bottom chopstick. In this paper, we use a method of real-time colliding face detection for polyhedral objects with complicated shapes [9].

If a collision occurs, all of the bending angles of the index, middle, and ring finger joints are maintained, and the displayed hand shape is generated instead of the sensor shape caused by the actual sensor data of the glove-type device. The chopsticks are aligned according to the displayed hand shape. This duplication continues until the collision/interference is over.

4. Interaction between Tool and Object

Two types of tests are introduced for the interaction between the tool and object, to compare each feature.

4.1. Simplified Interaction Test

Simplified interactions are expected to bring efficiency into the exchange for reality. For example, interactions using simple hand gestures and approximated object shapes enable a user to grasp or release a virtual object efficiently, e.g., the object is grasped if the representative point of his/her hand comes into the bounding sphere or box of the object and if he/she closes his/her hand.

A similar approach can be used in the interactions between the tool and object by introducing the chopsticks-pointer C, the middle point of the line connecting both tips of the chopsticks, and the bounding box of the object. The object is grasped if w becomes less than t while the point C is inside the bounding box of the object, where w is the distance between both tips of the chopsticks, and t is a threshold determined by an experiment (described later). On the other hand, the object is released if w becomes larger than $t + H$, where H is a value representing hysteresis to prevent object grasping and releasing in borderline cases.

4.2. Exact Interaction Test

An exact interaction test is introduced between the tool and object to achieve a realistic handling of the chopsticks. The object is grasped if it is sandwiched by the pair of chopsticks. If a collision occurs between a polygon of the bottom chopstick and a polygon of the object, the bending angles of the ring finger joints are maintained and the displayed finger shape is generated instead of the sensor shape caused by the actual sensor data of the glove-type device. If a collision occurs between a polygon of the a top chopstick and a polygon of the object, the bending joint angles of the index finger and middle finger are maintained and the displayed finger shapes are generated instead of the sensor shapes caused by the actual sensor data of the glove-type device. The object is grasped when both chopsticks collide with the object. The chopsticks are aligned according to the points P, Q, R, and S of the displayed hand shape. The object is released at the completion of one of the chopstick's collision/interference. Here, real-time exact collision detection is used among the polyhedral objects [9].

5. Experiments and Results

A Silicon Graphics Onyx2 workstation is used to control all of the input and output devices, and it displays position-tracked stereoscopic images. The user's eye position is derived from Polhemus Fastrack, a six-DOF magnetic tracker attached to Solidray LCD shutter glasses used for stereo viewing. The user can handle the virtual chopsticks; a Virtual Technology CyberGlove with 18 sensors captures the motion of his/her hand.

Figure 5 shows a snapshot of object manipulation with virtual chopsticks using exact interactions between the chopsticks and object (Venus with 1,816 polygons). Here, the detected pairs of polygons are shown by their color change to red. During the following experiment, 29.7 frames/sec was achieved if the simplified test was used for the interactions between the tool and object, while 16.8 frames/sec was achieved if the exact interaction test was used.

In the experiments, the simplified test and the exact test for the interactions between the tool and object were compared using a simple manipulation task and a precise alignment task of objects. Before the comparison, we made an experiment to determine the parameters for the simplified interaction test.

5.1. Parameter Determination for the Simplified Interaction Test

The simplified interaction test using a chopsticks-pointer and an approximated object shape employs threshold value t to determine the cases of object grasping and releasing. The object is considered grasped if the distance between both tips of the chopsticks becomes less than t while the chopsticks-pointer is inside the bounding box of the object. The purpose of this experiment is to find the best threshold value t that provides the user with the most intuitive interface.

The task is to sandwich a sphere with 11 different sizes (with a diameter from two to six centimeters) by the chopsticks and appeal when the user thinks he/she has grasped the object. The distance between the tips of both chopsticks (i.e., the grasping distance) is measured when the user appeals. The results from four subjects and two trials for each task are shown in Figure 6.

Equation (1) represents the approximate relationship between the diameter of the sphere (x) and the grasping distance (y).

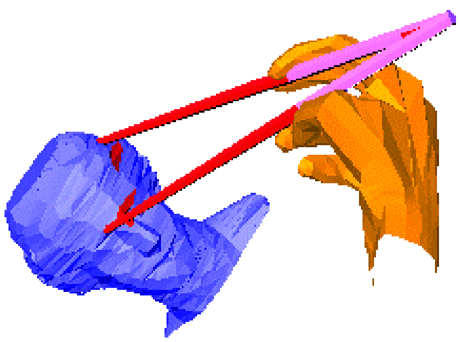

Figure 5: A snapshot of object manipulation using virtual chopsticks.

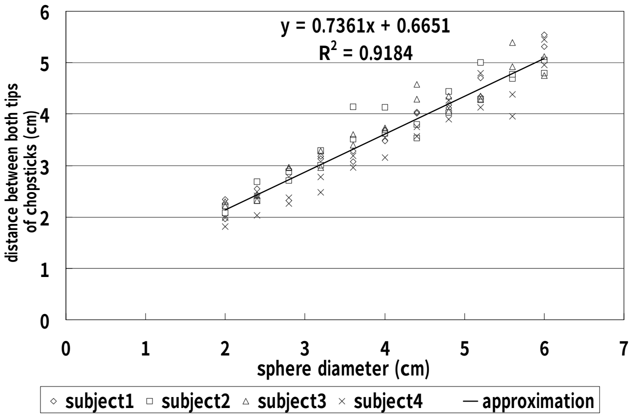

Figure 6: Grasping distance between the tips of both chopsticks against the diameter of the virtual object.

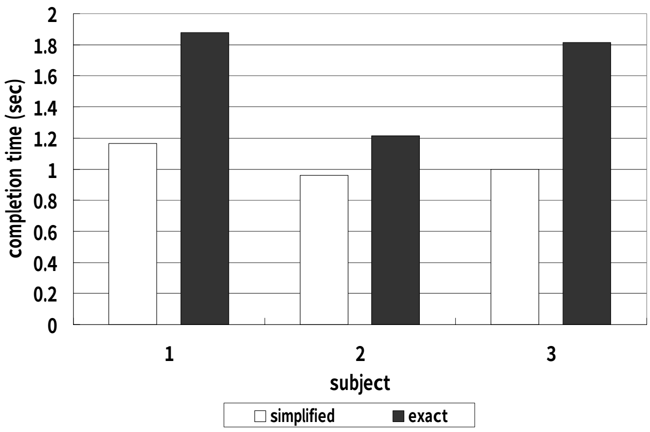

Figure 7: Completion time for a simple object manipulation task.

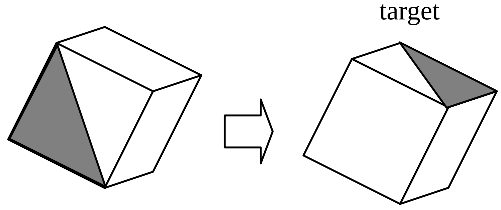

Figure 8: A precise object alignment task.

$$y = 0.736\,x + 0.665 \qquad (1)$$

The threshold value t is set equal to y derived from equation (1), and is used in the following object manipulation experiments. As described before, the object is released if the distance between the tips of both chopsticks becomes larger than $t + H$, where H is a value representing hysteresis to prevent object grasping and releasing in borderline cases. We use $H = 0.3t$ in the following experiments.

5.2. Simple Object Manipulation Task

A simple object manipulation task has been designed for comparing the simplified test and exact test for the interactions between chopsticks and object. The task is to pick up a sphere with a diameter of two centimeters located on the left side of the virtual environment, to move it to the right by crossing a wall, and then to release it. The subjects are asked to complete the task as quickly as possible. Ten trials are done for each subject and the task completion time is measured. The color of the object changes when it is grasped; however, the colliding polygons are not shown by their color changes in the exact test mode.

The average completion times for each manipulation for the three subjects can been seen in Figure 7. All of the subjects completed the task in a shorter time for the simplified test than for the exact test for the interactions between chopsticks and object. The simplified interaction is therefore efficient for simple manipulation tasks in which the user does not have to pay attention to adjusting the object attitude precisely.

5.3. Precise Object Alignment Task

Two precise object alignment tasks has been designed for comparing the simplified test and exact test for the interactions between chopsticks and object. The first task requires only translation; however, rotation is also required in the second task. Both tasks are to pick up a cube with a side length of two centimeters and to move it to the target cube aligning all eight corners as shown in Figure 8. Only a half of one face of the cube has a different color from the others. The subjects are asked to complete the task as accurately and quickly as possible. Ten trials are done for each task. Three measurements are taken: the task completion time, distance error, and angular error. Here, the angular error is the minimum amount of rotation that the manipulated object has to go through to the target around the center of gravity of the object [10]. The distance error is the distance between the centers of gravity of the manipulated and target cubes. The task is completed if the user releases the manipulated cube when the distance error is less than one centimeter or the angular error is less than 10 degrees.

Distance error and angular error versus task completion time for translation and rotation tasks performed by one typical subject are shown in Figures 9(a), (b), (c) and (d). The ellipses in these figures show the standard deviations for each axis with its center at an average value. The distance error and angular error for both the translation and rotation tasks are, on average, almost similar; however, the task completion times with the exact interaction are always less than those with the simplified interaction. This finding reveals that the exact interaction test contributes towards improving efficiency of the precise object alignment task.

Figures 10(a) and (b) show results from another typical subject. In these cases, the distance error, angular error, and completion time for the rotation task with the exact interaction are, on average, less than those with the simplified interaction. This finding reveals that the exact interaction test contributes towards improving both the accuracy and efficiency of the precise object alignment task requiring a six-DOF adjustment including translation and rotation.

This result corresponds to comments made by several subjects that they sometimes grasped or released object unexpectedly in the simplified test mode. This is because it was difficult to understand exactly when the chopsticks grasped or released objects with the simplified interaction test, while the exact point of contact on the surface of the object could be determined when the exact interaction test was used; therefore, they could precisely align virtual objects in the exact test mode.

6. Summary and Conclusions

A technique was proposed for object manipulation with a virtual tool using multiple exact interactions. Exact test was introduced that uses real-time collision detection for both hand-and-tool and tool-and-object interactions. The simplified interaction test using a chopsticks-pointer and an approximated object shape degraded the reality of object manipulation. The experimental results showed that it also prevented a precise task of object manipulation requiring the adjustment of many degrees-of-freedom (DOF) from being performed. However, it was efficient for simple manipulation.

On the other hand, the exact interaction test achieved the realistic handling of the chopsticks, and the users could manipulate the object precisely (with the exact test) for the interactions between the chopsticks and object, even if the task required a six-DOF adjustment including translation and rotation, because the users could determine the exact point of contact on the surface of the object.

The users of the virtual chopsticks system described in this paper are assumed to be able to handle chopsticks properly, because correct table manners are implemented. For people who cannot handle chopsticks properly, it is possible to apply the proposed method to a correctional system to rectify any incorrect handling. In such cases, a haptic display attached to the user's hand [11] may be useful; however, it would be necessary to identify the roles of each finger motion during chopsticks handling.

The implementation of other chopsticks' functions (e.g., cutting, tearing, flaking, peeling, scooping, wrapping, loading, pressing, pushing, splitting, piercing, and so on) involves a simple extension of the proposed exact interaction test. In addition, this framework can be easily generalized to other tools. One of our future goals is to investigate how virtual/real tools can help construct highly sophisticated mental models of users for tasks by limiting the possibilities of tool operations and functions.

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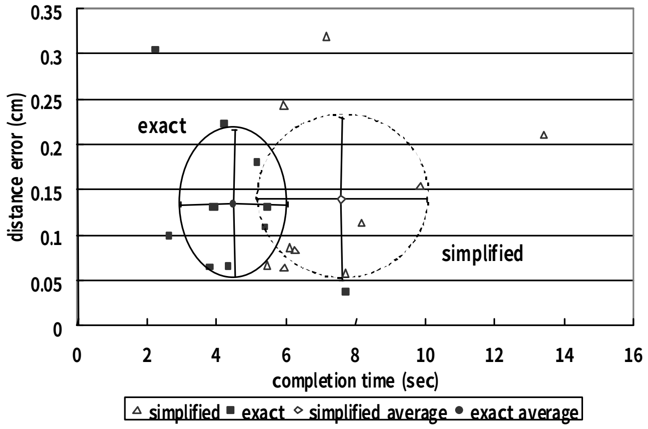
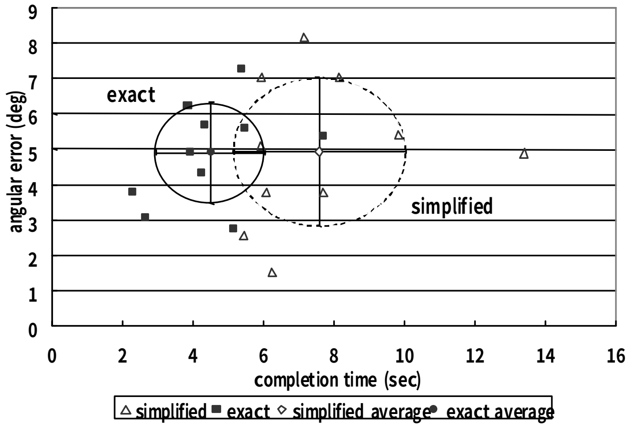
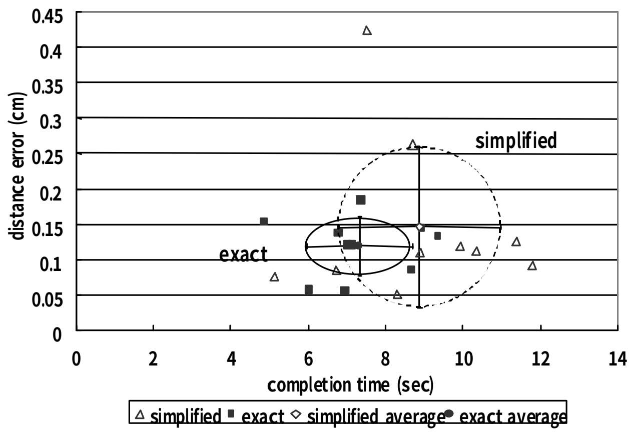


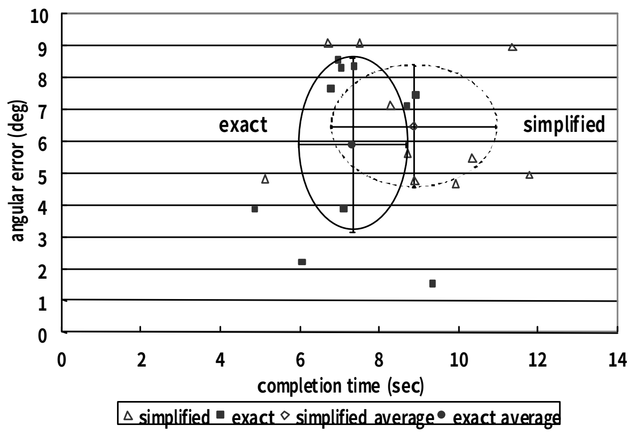
(a) distance error for translation task



(b) angular error for translation task

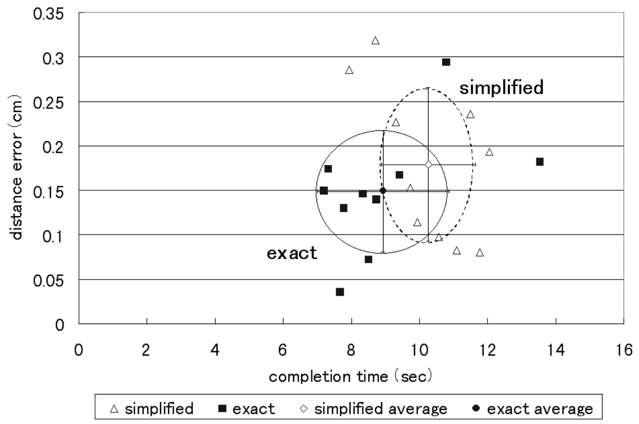


(c) distance error for rotation task

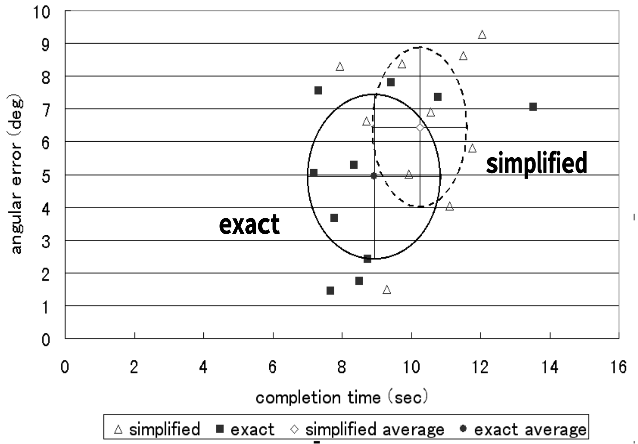


(d) angular error for rotation task

Figure 9: Distance and angular errors for translation and rotation tasks



(a) distance error for rotation task



(b) angular error for rotation task

Figure 10: Distance and angular errors for rotation task.