An Ungrounded Pen-shaped Kinesthetic Display: Device Construction and Applications

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ABSTRACT

In this paper, we implement an ungrounded pen-shaped kinesthetic display and construct a three-dimensional (3D) haptic interaction system. The ungrounded pen-shaped kinesthetic display provides kinesthetic sensations to a user's fingers without the use of mechanical linkages. Therefore, the user can move his/her hand freely in air and interact with virtual environments with sensation of touching. We verified the ability of the device to provide forces and to represent a virtual surface for 3D input. Then we constructed a 3D haptic interaction system in that the user can touch virtual objects displayed as 3D images directly. We also applied the device to an interface for 3D modeling and constructed a 3D haptic modeling system in that the user can create touchable 3D models by sketching two-dimensional (2D) figures in air.

KEYWORDS: Haptic interface, kinesthetic display, haptic interaction, 3D modeling.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 INTRODUCTION

In recent times, much research has been conducted on haptic interfaces. By integrating with three-dimensional (3D) displays, haptic interfaces realize users to touch 3D virtual objects and can improve existence of virtual environments. Many haptic interfaces have been proposed, and a pen-shaped haptic interface is one of major types of them. To use a pen-shaped device, a user is merely required to hold it and can interact with virtual objects with sensation of pecking or tracing by the tip of the pen. PHANToM [1] is a most popular pen-shaped haptic interface. PHANToM enables a user to perceive kinesthetic sensations on his/her hand with the help of mechanical linkages, which are driven by multiple motors. This device has been applied for many systems like 3D visual-haptic interaction systems [2] or 3D modeling systems [3, 4, and 5]. However, there is one unavoidable problem in using PHANToM as an interface; this device requires to be grounded to represent kinesthetic sensations, and therefore it restricts movements of the user's hand within the range of the linkages. When using grounded haptic interfaces like PHANToM, the user sees a monitor and move his/her hand at a position where the devices are placed and the user cannot touch displayed virtual objects directly. On the other hand, wUbi-Pen [6], ImpAct[7], and Senstylus [8] are ungrounded pen-shaped interfaces and can provide haptic sensations without limitations of hand movements. However, the wUbi-Pen and ImpAct are used while being touch with a screen surface and cannot be used for 3D spatial interactions in air. Senstylus, on the other hand, is a dual-rumble feedback device for 3D computer-aided-design (CAD) applications. The user can move their hand freely in air and manipulate 3D objects by his/her movements. However, the device can provide only vibrations as haptic feedback, which don't represent a realistic sensation of touching a 3D model. Although there are some ungrounded devices that are able to represent kinesthetic sensations on the user's hand [9, 10], they cannot provide continuous forces.

In our previous study [11], we proposed and prototyped an ungrounded kinesthetic pen-shaped display. The device does not restrict the movements of the user's hand and can provide kinesthetic sensations on the user's fingers. In this paper, we construct a device that has three motors inside it (Figure 1) and enable haptic interactions with 3D virtual objects in a physics-based simulation environment. We also evaluate the performance of the device for 3D input and construct a 3D modeling system in that the user can create 3D shapes by sketching two-dimensional (2D) figures in air.

Figure 1. Ungrounded pen-shaped kinesthetic display

2 UNGROUNDED KINESTHETIC PEN-SHAPED DISPLAY

In [11], we proposed a method to provide kinesthetic sensations to the fingers of a user without a use of mechanical linkages. To downsize the device, we hypothesized that kinesthetic sensations on fingers alone are sufficient to represent the sensations of touch. The proposed pen-shaped device consists of following two parts; a grip at the position where the pen is held by the user, and a base that is attached to the user's hand. The position where the base is fixed to the hand works as the point of support of force, and forces are provided on the fingers by moving the grip toward the base. We

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prototyped a pen-shaped device and confirmed that our proposed method were able to provide kinesthetic sensations and subjects could identify an increase in the provided forces.

This time, we designed and constructed an ungrounded pen-shaped kinesthetic display that has three built-in motors and an easy-holding fixture. Figure 1 shows the constructed device held by a user and Figure 2 shows the dimensional drawing of the body of the device. The body of the device was cast by using a rapid prototyping system (Dimension BST 768, Stratasys, Inc.). Three motors (Maxon Motor Corp., RE 10, 1.5W, gear ratio = 1:16) are placed parallel to the central axis of the pen. Strings are fixed to brass pulleys (6 mm across) using screws, and these strings are tied at the connecting points of the grip. The inner structure of the device is shown in Figure 3. When the motors rotate and connecting points are pulled up, the grip translates or leans toward the axis of the pen. A spring is placed in the base and pushes back the grip when the motors are not driven. The maximum force applied to the user using one motor is 4.9 N. We also designed a holding fixture and an openable and closable ring attached to the outside of the base so that the user can start using the device with little effort. To use the device, the user presses his/her index finger against the ring open. Then, the ring is closed and the index finger is fixed to the base.

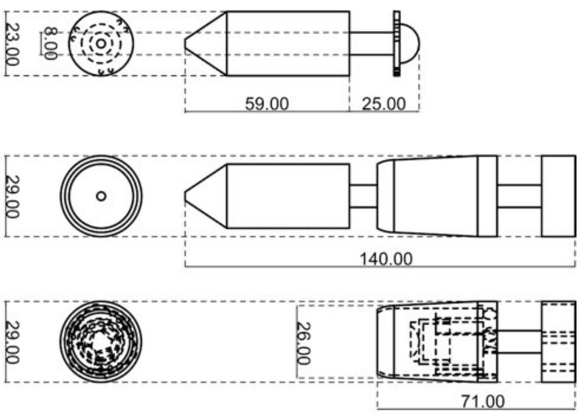

Figure 2. Dimensional drawing of the device.
The unit of measurement is mm.

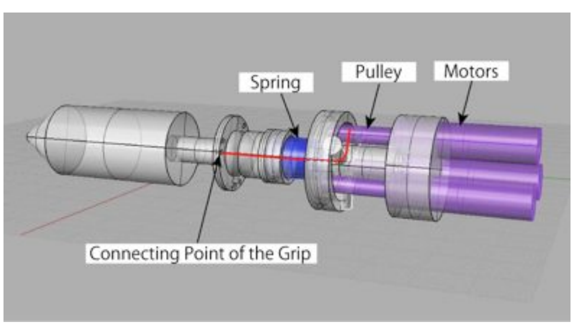

Figure 3. Inner structure of the device.
The red line shows a string.

3 DEVICE EVALUATION

3.1 Verification of Resolution to Provide Forces

To evaluate the representational ability of the constructed device, we conducted an experiment in that subjects compared two provided stimuli and answered which one was stronger.

This experiment was performed using a constant method. The subjects included four males and one female (in their twenties, right handed). In order to mask the sound of the motors, white noise was presented to both ears of the subjects via headphones. In this experiment, the subjects were instructed to hold the ungrounded pen-shaped kinesthetic display with their right hand and close their eyes. In each trial, a standard force and a comparing force were provided by the device in random order for one second at intervals of one second. Then, the subjects answered whether “the first force was stronger” or “the second force was stronger,” according to a two-alternative forced-choice procedure.

In this experiment, forces were provided in two conditions as shown in Figure 4. In the first condition, all motors of the device were driven and the grip moved parallel to the central axis of the pen. This motion generates the sensations of “pushing” or “pecking” virtual objects. In the second condition, one motor was driven and the grip moved perpendicular to the central axis. This motion generates the sensation of friction or the sensation of touching objects using the side of the pen.

In this experiment, the value of the standard force was set to 2.0 N, and seven values of the comparing force (0.8, 1.2, …, 3.2 N) were set. Twenty trials were performed for each condition of the value of the comparing force and the way motors were driven; therefore, each subject performed a total of one hundred and forty trials.

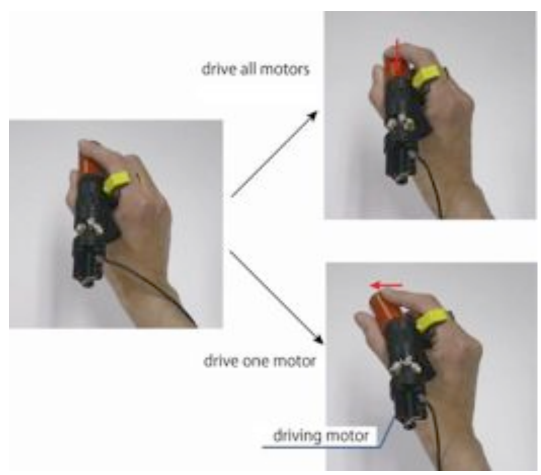

Figure 4. Motion of the grip in each condition of experiment

Figure 5 shows the rate of the responses that the comparing force was stronger than the standard force. The curves represent the fitted lines with a cumulative normal distribution. The point of subjective equality (PSE) is defined as the value of comparison stimulus that produces a rate of the answer corresponding to equiprobable random guessing (50 % for this experiment design). The difference between the PSE and the 75 % threshold is defined as the 75 % differential limen (DL). When all motors were driven and the motion of the grip parallel to the central axis of the pen was generated, PSE was 2.0 N and 75 % DL was 0.40 N. When one motor was driven and the motion perpendicular to the central axis was generated, on the other hand, PSE was 2.2 N and 75 % DL was 0.82 N.

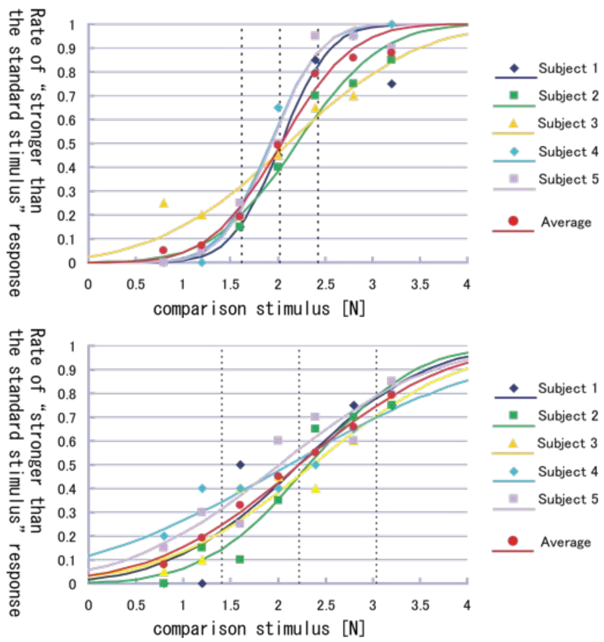

Figure 5. Result of force resolution experiment
(Top: driving all motors, Bottom: driving one motor)

3.2 Evaluation of Application Possibility to 3D Input

We performed another experiment to evaluate the ability of the constructed device to help 3D input by kinesthetic feedback. By using a physics simulation engine, we constructed a virtual environment and presented a virtual canvas in air.

For this experiment, we constructed a prototype haptic interaction system that enables the user to touch virtual objects with the ungrounded pen-shaped kinesthetic display. Figure 5 shows an external appearance of the system. The size of the booth is 90 x 90 [cm]. Six infrared cameras (OptiTrack FLEX: V100, NatuarlPoint, Inc.) are placed at the top of the booth and the position and the pose of the device are tracked by capturing three markers fixed to the pen (see Figure 1). A 24-inch monitor is placed and the user can see virtual objects placed inside the booth. The virtual environment is constructed by using a physics engine PhysX [12], and contacts between objects and the tip of the kinesthetic display are simulated. ContactReport class of PhysX calculates 3-DOF contact forces. And based on the calculated forces, kinesthetic sensations are represented on the user's fingers by driving the motors in the device. In this system, virtual objects and the pen-shaped proxy that represents the kinesthetic display are displayed on the monitor. The user can control the proxy by moving his/her hand inside the booth, and touch virtual objects as if the displayed objects exist in the real environment.

Figure 7 shows the setup for the experiment. For the experiment, we placed a virtual canvas, which was with the size of 50 x 50 [cm] and was inclined toward the monitor at a 30-degree angle, at the center of the booth. A circle, which was 30 cm in a diameter, was displayed on the face of the canvas, and three subjects were instructed to trace it with the device in each trial. The subjects included two males and one female (in their twenties, right handed). White noise was presented to both the ears of the subjects via headphones, which masked the sound of motors. Three trials were performed for each condition of with or without kinesthetic feedback. Therefore, each subject performed six trials.

Table 1 shows the average RMS (Root Mean Square) of overshoots of the tip of the device from the surface of the virtual canvas. The average RMS of all subjects was 52 mm in the case with kinesthetic feedback, and was 127 mm in the case without kinesthetic feedback.

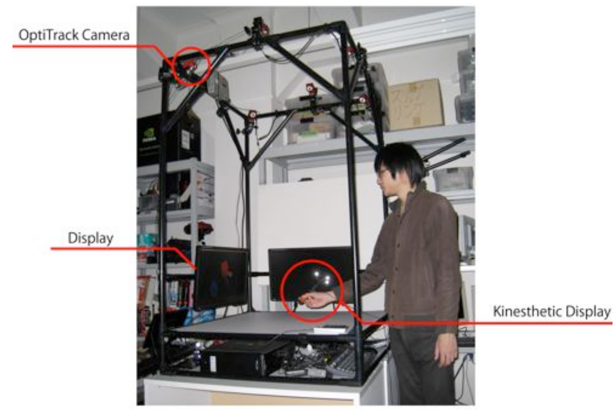

Figure 6. Prototype haptic interaction system

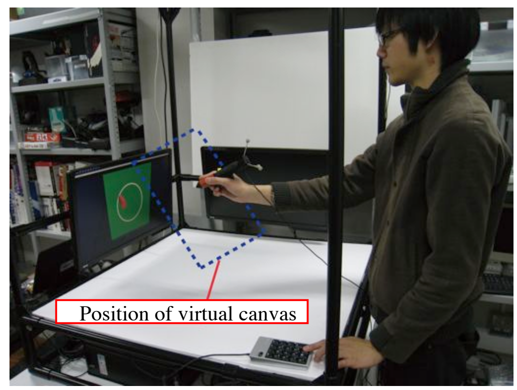

Figure 7. Setup for 3D input experiment

Table 1. Result of 3D input experiment [mm]

	subject1	subject2	subject3	average
without Force	±172	±140	±72	±127
with Force	±15	±88	±54	±52

3.3 Discussion

As shown in the results of the force resolution experiment, it was confirmed that the constructed ungrounded pen-shaped kinesthetic display can apply multilevel forces to the fingers. The device can apply forces of 14.7 N at the maximum in a direction parallel to the central axis of the pen by driving all motors. Therefore, the device has a high resolution and a maximum value to provide forces in this direction. However, our proposed device provides kinesthetic sensations to fingers by moving the grip and the range of movement of the grip has a limit. The maximum value of force that the user can perceive must be measured as a future work. On the other hand, one or two motors are used to provide forces perpendicular to the central axis, and therefore, the maximum value of the forces in this direction is smaller. In addition, the results of the experiment show that the resolution to provide forces in the direction perpendicular to the central axis is lower and the device can apply force of levels with small numbers in this direction. There are differences in the effectiveness of force provision among individuals because the fixation of the base of the device to the hand is easily effected by how the user holds the device. In the future work, we will design a holding fixture that can be held more easily and firmly by different users. However, the constructed device will work to some extent for representing virtual objects with multilevel hardness and friction.

In the 3D input experiment, contact forces between the tip of the pen and the virtual canvas were provided. PhysX simulated contacts between rigid bodies in the simulation environment and the subjects could feel as if they were touching a rigid canvas. In addition, 3-DOF forces were provided and the subjects could recognize leanings of the canvas with kinesthetic feedback. Figure 8 shows examples of the transitions of overshoot in trials of the 3D input experiment with kinesthetic feedback (shown as a red curve) and without kinesthetic feedback (shown as a blue curve). This graph shows the effectiveness of kinesthetic feedback with the ungrounded pen-shaped kinesthetic display to represent an input surface in 3D manipulations. These results of this experiment encouraged us to construct a 3D modeling system that supports the user's manipulations by representing a virtual input surface with kinesthetic feedback. With the use of the ungrounded pen-shaped kinesthetic display, intuitive input manipulations in air will be achieved.

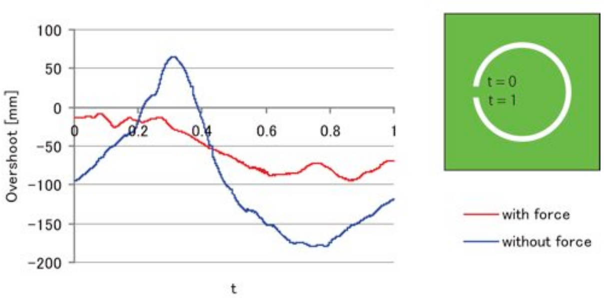

Figure 8. Example of motion trajectories in 3D input experiment (performed by subject 3)

4 3D Haptic Interaction System

The proposed device can provide kinesthetic sensations to the user's fingers without the use of mechanical linkages and this advantage is useful to realize direct interactions with 3D images. In this chapter, we construct a haptic interaction system (Figure 9) in that the user can touch virtual objects by using the constructed kinesthetic display. We display the virtual environment with 3D image display. Hence, the user can see virtual objects as 3D images and touch or move them with kinesthetic feedback.

We constructed the haptic interaction system based on the prototype system constructed in section 3.2. The virtual environment is constructed using PhysX, and contact forces are calculated for kinesthetic feedback. The position and the pose of the device are tracked by OptiTrack cameras, and the motion of the user's hand is reflected to the virtual environment.

To display the virtual environments with 3D image, we implemented a chassis with a 40-inch screen and projected images by a projector placed inside the chassis. The user can see 3D images on the screen by wearing 3D glasses (3D Vision, nVidia Corp.). We placed three markers on 3D Vision and tracked its position with OptiTrack cameras placed around the chassis, and displayed images appropriate to the user's eyes. Therefore, the user can see virtual objects from various directions and touch them with the ungrounded pen-shaped kinesthetic display as though they were floating in air.

In this system, the user can touch displayed 3D images directly with sensation of touching. This feature improves the existence of virtual objects efficiently compared to the prototype system with 2D images. When the proxy that represents the position of the tip of the device in the virtual environment is not displayed, the user can feel as though he/she were touching objects that existed physically in the real world.

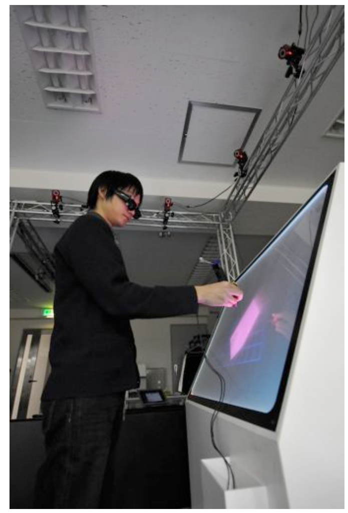

Figure 9. 3D haptic interaction system

5 3D Haptic Modeling System

The haptic interaction system constructed in chapter 4 encouraged us to apply the ungrounded kinesthetic display to a system in that the user can create and manipulate 3D objects directly in air. In this chapter, we construct a 3D haptic modeling system by integrating the haptic interaction system with a 3D modeling software. To enable an easy and intuitive 3D modeling, the manipulation that the user has to perform to create 3D shape should be as simple as possible. Therefore, based on the result of the experiment in section 3.2 and the modeling method of Teddy [13], we realized a 3D shape creation by drawing 2D figures in air.

We support the user to draw figures in mid-air by reproducing the virtual canvas as done in the 3D input experiment. We placed an input button at the grip of the ungrounded pen-shaped kinesthetic display and enabled to switch operations by pushing or releasing the button. When the user pushes the button for the first time, the virtual canvas appears at the tip of the pen. The position of the device is tracked by using OptiTrack cameras, and the user can place the virtual canvas at a desired position by moving his/her hand. The virtual canvas is generated in the physics-based simulation environment and displayed as a 3D image. When the user touches the canvas, the ungrounded pen-shaped kinesthetic display generates reaction forces calculated by PhysX based on the degree of the contacts. Therefore, the user can draw 2D figures on the virtual canvas as if he/she were drawing on a real canvas with physical existence.

We implemented an operating panel for 3D modelling (Figure 10) and placed it in front of the chassis. To create a new shape, the user selects the desired shape from among a sphere, a box, and freeform surfaces. Then the user sketches a 2D figure of the desired shape on the virtual canvas, for example, a circle, a rectangle, or a free closed curve. The motion trajectory of the tip of the pen is recorded while the input button is pushed and held. Based on the tracked trajectories, parameters of the shape are calculated and the desired shape is created in the environment. Figure 11 shows how 3D shapes are created from motion trajectories. By these implementations, touchable 3D shapes were successfully created by an easy operation of sketching 2D figures in air.

We also implemented sketching in air without the virtual canvas in addition to sketching with canvas described above. In this mode, the user can sketch figures directly in the air by holding the input button and moving his/her hand. A constant force is provided to the user's fingers while the button is pushed and held as if the user were sketching figures on an invisible canvas. The tracked motion trajectories are fit to a surface with a least square algorithm and parameters of the desired shapes are calculated.

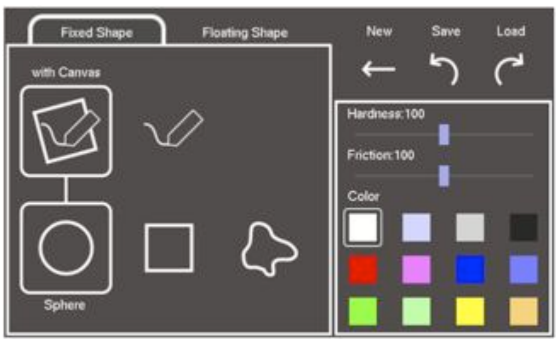

Figure 10. Operating panel

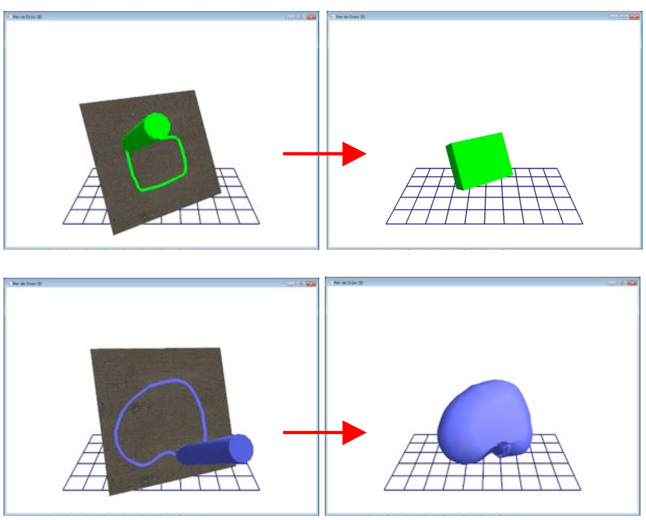

Figure 11. Creations of shapes from motion trajectories (Top: Box, Bottom: Shape with freeform surfaces)

Figure 12 shows the constructed 3D haptic modeling system. The user wears 3D glasses, holds the ungrounded pen-shaped kinesthetic display by his/her right hand, and stands ahead of the chassis. Then, the user touches the operating panel to select the desired operations. The user can also configure the color, hardness, and friction of the shape. Then the user draws 2D figures on the virtual canvas or in air, which are converted to 3D shapes. By combining multiple shapes, the user can create complex 3D models easily. The created 3D models can be seen from various directions and be touched by the ungrounded pen-shaped kinesthetic display. The values of the hardness and friction of the shapes are reflected to forces calculated by PhsyX as factors. The user can confirm shapes and haptic impressions of the models or interact with them. Figure 13 shows an example of 3D models created by using this system.

In the prototype haptic interaction system constructed in section 3.2, the 3D virtual environment was displayed on the 2D monitor. Therefore, the subjects of the experiment were not able to estimate the position and the pose of the canvas placed in the booth accurately without kinesthetic feedback provided by the ungrounded pen-shaped kinesthetic display. We constructed the haptic modeling system with kinesthetic feedback and 3D image display. This integration realized the intuitive manipulation as if the user were drawing a canvas that existed in the real world. The representation of the virtual canvas is effective not only for intuitive input manipulation but also accurate model creations; the user can coordinate the position of shapes where they will be generated by moving the canvas. This position coordination method is more intuitive than methods used in conventional modeling systems and the user can design 3D structures of the models easily by using the system.

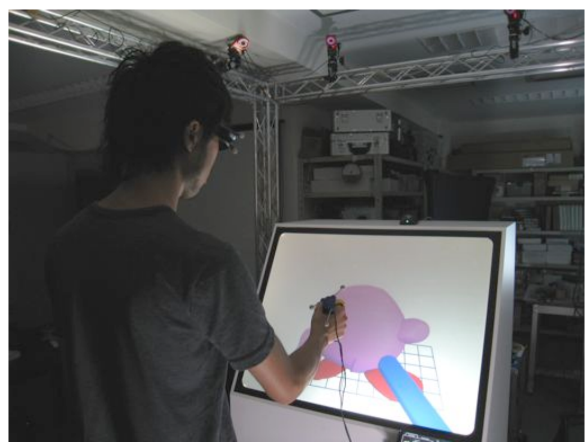

Figure 12. 3D haptic modeling system

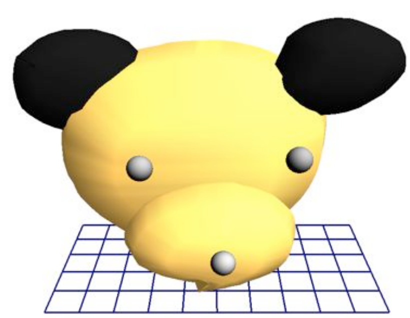

Figure 13. Example of 3D models created by using the system

6 CONCLUSION

In this paper, we implemented an ungrounded pen-shaped kinesthetic display and constructed two haptic-enabled systems; a 3D haptic interaction system and a 3D haptic modeling system. Based on the previously-proposed method, we implemented the device that provides kinesthetic sensations to fingers and verified the force resolution and the application possibility to 3D input of the device. Then we constructed a system in that a user can see and touch 3D virtual objects with sensation of touching. We also applied the device to 3D modeling, and constructed a system that enables the user to create touchable 3D shapes by sketching 2D figures in air with kinesthetic feedback.

As the proposed device does not impose restrictions on the user's movements, it can be used in more space than conventional kinesthetic displays. And also, multiple users can use the devices respectively at same time in same place because each device works without interferences. Taking advantage of these features, we are planning to construct a system in that multiple users can enjoy or work together in virtual environments. The constructed 3D haptic interaction system that improves existence of virtual objects encouraged us to develop some interactive applications for communicating with virtual creatures. Additionally, more intuitive 3D modeling methods can be proposed as future works. In the constructed 3D haptic modeling system, the user can only create shapes and turn off a 3D model by putting them together. We intend to implement transforming manipulations on shapes by pushing or scarping with kinesthetic feedback. We will also implement alternative methods to create shapes by sketching, for example, combining two figures to create oval sphere or complex box shapes or indicating a surface of the shape by drawing spirals.

ACKNOWLEDGEMENTS

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