1 DOF Tabletop Haptic Mouse for Shape Recognition of 3D Virtual Objects

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Abstract—In this paper, we propose a 1 Degree-Of-Freedom (DOF) mouse- shaped haptic device for shape perception of 3D virtual objects. Decrement of DOF of haptic device brings advantages, such as a miniaturization, solidity, and a weight reduction. A 1 DOF haptic device that consists of a built-in optical shaft encoder, two position sensors and a motor, has been developed. This device is easier to integrate with a tabletop system compared to multiple DOF haptic devices. We propose some haptic algorithms, which are effective to 1 DOF haptic device, and two types of pointing environments with a multi-touch overlay. Some experiments were conducted to evaluate the effectiveness of the proposed system. The elements required to make the system functional were clarified.

Keywords-1 DOF;Mouse Device; Haptic; Image Display; Direct Pointing; Multi-touch Overlay

I. INTRODUCTION

Many haptic devices have been used in the field of 3D shape modeling. They make it possible for users to design virtual characters with intricate shapes, and so on. However, because most haptic devices have multiple DOFs, they tend to be bulky, heavy and expensive. Also, their control algorithms become complex. These factors obstruct the use of haptic devices in general. In terms of the operation of a GUI, we believe that adding 'force feedback' to a tabletop display system is an effective way of further improving its usability and of enhancing its own powers of expression. However, it is difficult to integrate multiple DOF devices with a tabletop display interface because the hardware that is required is quite bulky. We considered that a reduction in the number of degrees of freedom of the haptic interface could be one solution to overcome this issue, since the further the number of degrees of freedom of the haptic device can be reduced, the simpler the hardware that is required becomes.

In 3D shape modeling, we initially not only observe, but also touch the surface of a virtual object to recognize its shape precisely. If a user touches a virtual object on a tabletop display, the user will expect to feel the unevenness of the object. In this process, we assume that there is a principal force vector that is incorporated in the shape recognition process. In order to feel information concerning the unevenness of the surface, depth information regarding the virtual object is a key element in shape recognition. Therefore the 'up-and-down' direction force vector is chosen to present depth information on a tabletop display in this study. As shown in Figure 1, a user can get a sense of touching a virtual object by raising or lowering their fingertip according to the unevenness of the virtual object with visual feedback.

In this research, we developed a prototype system that consists of a 1 DOF mouse-like haptic device and a tabletop display with a multi-touch overlay sensor. The haptic device is small and safe to use. It has the ability to present an 'up-and-down' force to the user's fingertip. It can be controlled in a stable manner by using a simple control algorithm. In addition, we realized a "What You See is What You Touch" (WYSWYT) environment as the pointing environment. In this system, the user can see virtual objects and can also touch the virtual objects directly with his/her fingertip. A number of experiments were conducted to demonstrate the effectiveness of the system.

The remaining of the paper is organized as follows. Section II describes related work. Section III describes the design principle of a haptic interface. Section IV describes the system configuration of our prototype system and its haptic rendering algorithm. Section V describes an evaluation experiment conducted and its results. Finally, the results are discussed in Section VI before concluding.

II. RELATED WORK

Akamatsu reported that providing the sensation of touching a virtual object by imparting vibration to a user's index finger on a mouse interface in a GUI environment is effective for reducing the completion time of a pointing task [1]. Fukunaka proposed a method of presenting a sense of resistance or confliction by using a mouse-shaped device containing a magnetorheological fluid (MR fluid) [2]. However, these devices cannot present the reaction force from the virtual object. They can only present a sense of vibration or collision.
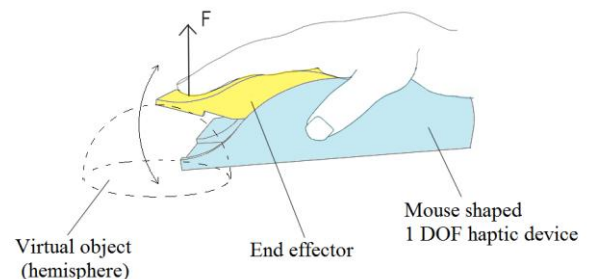

Figure 1.   Virtual object presentation by haptic mouse

Marquardt reported how adding a haptic layer to the interactive surface experience can augment the existing visual and touch modalities by using a "haptic tabletop pack", which can present vertical relief, malleability of materials, and horizontal friction on the surface [3]. But it cannot present shape of the virtual object.

Howe et al. developed the first motion compensated actuated catheter system that enables haptic perception of fast moving tissue structures for surgery of the beating heart. This system enables physicians to operate on the beating heart without caring about deformation of the heart caused by the heart beating, but this system does not enable the user to perceive its shape[4].

The "Touch the Untouchable" system has been developed as an example of a 1 DOF haptic device. This device measures the distance to a remote object by using a laser range sensor, and presents the shape of the object by using the distance data [5]. Alternatively, the "Beyond" system can present virtual objects beyond the display by using a pen-shaped device [6].

The above studies did not reveal a haptic rendering method for complex shaped virtual objects, or consider the influence of reducing the number of degrees of freedom of the interface device. In this study, a prototype 1 DOF haptic mouse has been developed that is suitable for use on a tabletop display. By using this mouse, the effectiveness and limitations of this method were evaluated through a number of experiments.

III. DESIGN PRINCIPLE

In this study, even though the number of degrees of freedom of the haptic device were reduced, we assumed that the 'visual dominance' effect imparted by the users could assist the user's shape recognition process. Therefore, as a visual display system, a tabletop GUI environment was selected.

Since the tabletop environment is a flat surface display, the motion of a haptic device on the tabletop is limited by the surface. By combining the limited horizontal motion and depth (up-and-down) motion of the haptic device, the user can recognize the shape of a virtual object stably.

Tabletop haptic interface requires small size, high accuracy, high speed measurement of a user's fingertip position, and sufficient output torque. Furthermore, we assumed to use this device on a tabletop display with visual feedback. Therefore its movable area should be greather or equal to the area of the display area

In order to accomplish this specification, we designed a prototype un-restraining device with built-in sensors and an actuator to securing large movable region. Considering to use the device on a display, the screen of the display should not be coverd over by the device. Hence, a pen shaped device and mouse shaped device can be considered as a structure. However, it is difficult to build in an actuator which can generate sufficent torque on the pen shaped device. Therefore the mouse shaped device, which can store various modules underneath the user's palm, was used in this study. In order to realize a simple and robust mechanism, the haptic device consists of an end effector, a position sensor, a control

PC, and a visual display. The end effector is a lever that can be rotated around a horizontal axis by a DC servomotor so that it can generate an up-and-down force directly to the user's index fingertip. The range of up-and-down motion of the end effector is about 60 mm, taking into account the range of movement of the index finger. The end effector and its base should be transparent to avoid hiding the visual image on the display. An accelerometer, a camera with image processing, an optical mouse sensor are candidates for the position detection sensor. Since the accelerometer has undesireable drift characteristics, and the camera is bulky, two optical mouse sensors are used in this study. They can be measure the position and orientation of the mouse device in un-restraining manner. Also they are cheap and has easy to operate. Moreover the position of the fingertip on the display should be detected without hiding images under the end effector. Therefore, unlike a conventional mouse, neither a position sensor for the mouse nor a stylus could be placed under the end effector. Hence, it is necessary to detect both position and orientation when using this system to calculate the fingertip position. Therefore, 2 sensors are required to detect both position and orientation. However, since the optical sensors can detect only the relative position change of the device, the precise absolute position of the mouse on the display is unacquirable. The direct pointing environment, which is one of the purposes of this research, is difficult by using the sensors. A method to measure the absolute position by using an infrared multi-touch overlay is mentioned later.

IV. 1 DOF HAPTIC MOUSE

A. System configuration

Figure 2 shows an overview of our prototype for a 1 DOF haptic mouse system. The system consists of a haptic mouse unit, a position detection unit, a control unit, and a PC (OS Windows7 Professional 64bit CPU IntelCorei5 650).

The haptic mouse unit is composed of just a geared(gear ratio 5:1) DC servomotor (*RE25*, made by maxon Inc) and an end effector. Since the gear ratio is small enough, the user can move an index finger up-and-down without feeling resistance. The end effector makes contact with the tip of the user's index finger. It rotates around a horizontal axis so that it moves the user's index finger vertically, as shown in Figure 1. The height of the fingertip is calculated from the value of the optical shaft encoder in the motor. The maximum force on the fingertip is 8 N. Two optical mouse
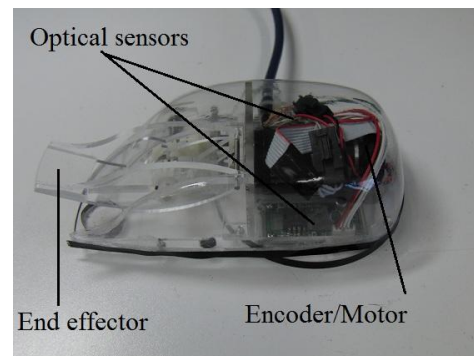

Figure 2. 1 DOF haptic mouse

sensors (made by PixArt Imaging Inc) were used to maintain operability as far as possible. By obtaining the values from the sensors and taking their difference, the relative position and orientation of the device can be calculated. There is an accumulation error of about 4% in terms of the migration distance.

As the control unit, the "Device Art Toolkit" [7] was used to control the optical mouse sensors and the motor of the mouse. This is a controller in which the user can freely change the number and the function of the input-output channels by plugging in various module boards. In this research, a serial communication module, an encoder counter, a PWM output for controlling the motor's output torque, and a motor driver were used.

B. Haptic Rendering Algorithm

1) Penalty method

In this research, we presented a reaction force in the vertical direction based on the 'penalty method'. As shown in Figure 3, the reaction force was calculated by adding a reaction force and an impulsive force. The reaction force is proportional to the penetration depth (difference between the height of a virtual object and the height of the fingertip position). The impulsive force is proportional to the penetration speed to the object (Equation 1);

$$F = K_p(Z_{obj} - Z_{fin}) + K_d(Z_{fin} - Z_{fin\_p}) \qquad (1)$$

where Z_{obj} means the height of the virtual object at the current fingertip position, Z_{fin} means the height of the current fingertip in the case where $(Z_{obj} - Z_{fin}) > 0$: $K_p > 0$. In other cases, $K_p = 0$, Z_{fin_p} means the height of the fingertip in one program loop, in the case of $(Z_{fin} - Z_{fin\_p}) > 0$ and $(Z_{obj} - Z_{fin}) < 0$: $K_d < 0$, in other cases: $K_d = 0$.

A typical example of the locus during touching of a virtual object using the haptic mouse is shown in Figure 4. The green line indicates the locus of the user's fingertip during operation. You can see that the fingertip was moving on the object's surface.

2) Haptic rendering technique using height map data

This system can render a virtual object with haptic sensation by using data from a height map, as opposed to the fundamental haptic rendering method using virtual objects defined by some equations or polygons. Since this system renders a virtual object by using only 1 DOF for the upward reaction force, it is possible to render an object by using the height information of the object corresponding to the
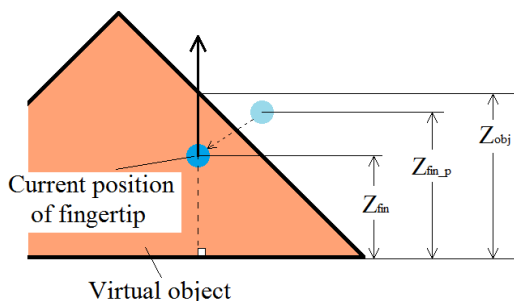
two-dimensional coordinates on the display surface. We achieved haptic presentation using a height map by utilizing this technique.

A height map records height information as brightness information at each pixel of the image. If the color of a pixel is close to black, the height is low. If the color is close to white, the height is high. This system can present a reaction force by using the penalty method described in the previous section by analyzing 24bit bitmap image data. It is possible to render a complex shape of a virtual object by using this technique, even if the shape is difficult to define using equations or a polygon model, as shown in Figure 6.

3) Haptic rendering method of a virtual wall that is perpendicular to the ground

When rendering a shape like a cube, which has side surfaces perpendicular to the ground, the user's fingertip is forced to move rapidly upwards. Sometimes this may cause an unwanted vibration and make the user feel uncomfortable. In this study, some small steps were placed on the surfaces to overcome this incongruity. After trial and error, the size of the small steps was set to 1 mm in width and 20 mm in height to reduce the unwanted vibration. The user's fingertip climbs up two steps in a very short time if the virtual wall has a height of 40 mm.

Figure 6 shows a typical locus of a user's fingertip with the haptic mouse when he touches a virtual cube from left to right. By using the proposed technique, the heights of the overshoots are reduced compared with a method that does not include the small steps described in previous section. When the fingertip moves from the upper surface of the cube to the ground, the end effector falls slowly according to the input force at the fingertip. This causes the gently-sloping trajectories on the right side of the cube that are shown in Figure 6.
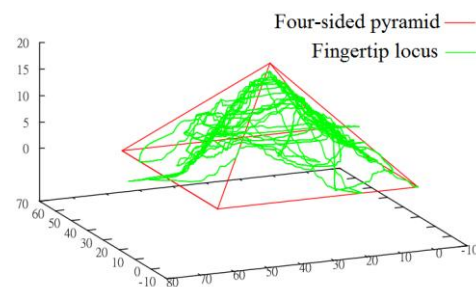

Figure 4.   Typical locus of fingertip during touching a virtual pyramid

Figure 5.   Haptic rendering with a height map data

Figure 3.   Concept of the penalty method

V. 1 DOF HAPTIC MOUSE WITH MULTI-TOUCH OVERLAY

When using the developed 1 DOF haptic mouse, the spatial relationship between the visual presentation and the haptic presentation was in agreement, and it was thought that presentation closer to the appearance of a real object would be realizable by building a direct pointing environment in which a haptic presentation is shown when touching a visual representation with direct feedback. In this research, in order to harness the characteristics of a 1 DOF haptic mouse that is not grounded, a direct pointing environment was created by combining it with an infrared multi-touch overlay that can detect the positions of two points in an unrestrained manner (Figure 7).

A. Adding a multi-touch overlay for precise measuring

A multi-touch overlay (made by PQLabs) was used in this section. Although the position of an object on the display could be detected accurately by using the multi-touch overlay, there was a time delay of approximately 0.15 s. Since the response of the multi-touch overlay with the infrared sensor was insufficient, we added positional data from the optical mouse sensors during the preceding 0.15 s to the positional data from the multi-touch overlay. In this way, the sensor can avoid an accumulation of errors from the optical sensor, and real-time precise measurements could be realized on the tabletop system. Figure 8 shows a typical measured trajectory of the mouse by using the proposed method at a velocity of 100 mm/s, which is the average velocity when virtual objects are touched by users. The measured data is almost the same as the true trajectory. However, if the velocity is increased to 250 mm/s, approximately 20 mm of overshoot is observed when the mouse decelerates to a halt (Figure 9) due to the delay of the multi-touch overlay. In normal usage, this does not become a concern, since the user does not touch a virtual object at such a high speed or does not stop the mouse suddenly.

The system can measure the position of the fingertip with high precision in real time. The frequency of the measurement was about 1 kHz.

B. Comparison of direct pointing with indirect pointing

An experiment was conducted to evaluate the effects of differences in the pointing environment when using the developed system. In a feasibility study, some users reported that they felt the sense of the presence of the displayed virtual objects with the direct pointing environment
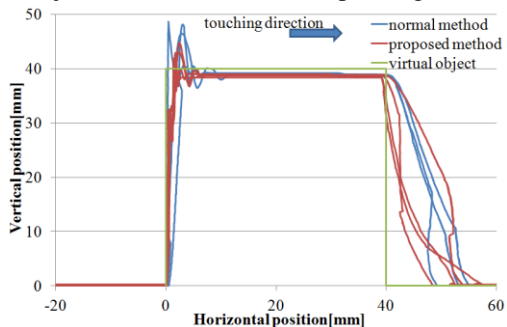
compared to the indirect one.

Therefore we aimed to reveal the key issues of the different feeling in this experiment.

1) Experimental details

Subjects were asked to perform the task of tracing round a virtual Torus-like object, and their EMG data were recorded, the operation time, the pressure on their fingertip, and the operating locus. In this experiment, 'direct pointing' means a state in which the pointing position on the virtual plane and the position of the subject's fingertip corresponded without displaying the pointer, while 'indirect pointing' means a state in which the position did not corresponded with the displayed pointer (Figure 10). EMG data were measured using an electromyograph (*Active Two*, made by Biosemi) fitted around the extensor digitorum muscle and the flexor digitorum superficialis muscle, which both contribute to the operation of the index finger. A pressure sensor (*FlexiForce*, made by TECKSCAN) was stuck onto the end-effector, and the pressure on the fingertip was measured. Six male subjects conducted 3 trials each under each of these conditions. The order of presentation was randomized in order to negate the influence of the order of the tests.

2) Results

The average of all subjects' operating time is 11.891 seconds in the indirect pointing and 10.745 seconds in the
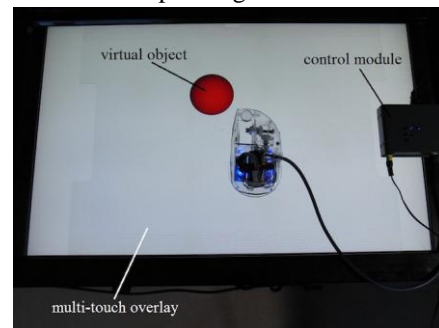

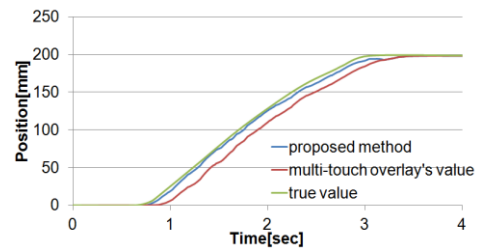Figure 7.   System overview of tabletop haptic interface

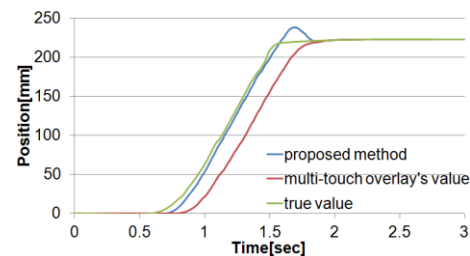Figure 8.   Position detection with two kinds of sensors (100mm/sec)

Figure 9.   Position detection with two kinds of sensors (250mm/sec)

Figure 6.   Typical locus of a user's fingertip during touching a virtual cube

direct pointing. Operating time was slightly shortened in the direct pointing but there was no significant difference. The average error between each position of a fingertip and target position (peak of Torus) was 2.017 mm in the indirect pointing and 2.112 mm in the direct pointing respectively. Although there was slightly difference of error value between each pointing environment, there was no significant difference.

The root mean square (RMS) values of the EMG measurements were determined in order to perform a waveform comparison. The resulting data was smoothed using a moving-average interval of 200. Moreover, in order to negate the differences between subjects, the peak value of the EMG data for each muscle in the indirect pointing environment was made equal to 100%, the EMG was normalized, and was also normalized with respect to operating time. Next, a conventional 't test' was performed to investigate the difference in EMG for the different types of pointing environments.

Figure 11 shows the average time series of the EMG of the flexor digitorum superficialis muscle obtained as a result of the experiment. The values of EMG, for indirect pointing were stronger in the flexor digitorum superficialis muscle (t = 15.7969, df = 17987 p < 0.01). This means the subjects tended to press the object firmly in the indirect pointing environment. Also, we noted a significant difference in pressure (t = 17.1802, df = 17987 p < 0.01); stronger pressure occurred at the fingertip for the indirect pointing environment. This result is consistent with the EMG data.

In this experiment, the subjects should pay attention to move the mouse pointer on the center of the arc of the virtual circular ring. The subjects tended to place the pointer at the center by using visual information usually. In addition, haptic feedback gave additional information to the subjects. The reaction force rapidly decreased out of the center. If the subject pressed the ring harder, he/she could discriminate the position change easy.

In the indirect pointing environment, since the subjects watched the display and couldn't watch their own hand, which held the mouse, they tended to use not only the visual information but also the haptic information. On the other hand, in the direct pointing environment, the subjects were easy to adjust the position of the mouse by watching their own hand.

These caused the results that the pressure and the EMG in the indirect environment were larger than these in the direct one. In addition, in the direct pointing environment,
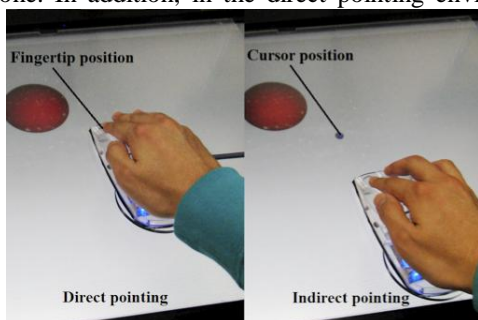
the subjects tended to press the ring lower pressure at the left or right edge (time of 25% or 75%). Because the ring extends up-and-down direction at these points, the subjects could adjust the position of the fingertip easy.

Moreover, when the subjects were asked to give their impressions after the experiment, a variety of opinions were expressed as to which environment the operativity best supported; the overall opinion was that both environments were almost the same.

VI. DISCUSSION

When compared with an indirect pointing environment, it turned out that the EMG generated in the flexor digitorum superficialis muscle and the pressure on the fingertip in the direct pointing environment were lower. Since the portion of the finger that was directly touching the object in this situation was hidden like it is in the real world, it was believed to influence the subject to touch more carefully.

In the operation of a two-dimensional vision display, it has been reported that, when making a comparison between an indirect pointing environment using a pointing device and a direct pointing environment in which the target is touched with a finger, the direct pointing is superior in terms of operating time and operability [8]. However, there is no significant difference in terms of operating time or the locus of operation in this study. A direct pointing environment has predominance when operating using vision alone, but when haptic presentation is also involved, it can be said that differences in the pointing environments do not have a big influence on the performance of haptic presentation. The direct pointing environment has advantages. It enables a user to touch an object by using his/her own fingertip similar to the real world. Also the user can perceive the shape of a virtual object by combining the device and a real object such as a ruler and so on. However, since implementation of direct
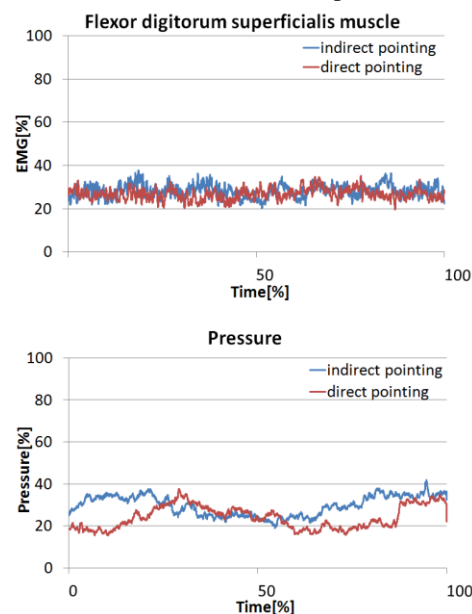

Figure 11. Time series valuation of the average EMG of the flexor digitorum superficialis muscle (top) and average pressure on the end effector of the haptic mouse (bottom)

Figure 10. Experimental environment

pointing environment is required capabilities of high accuracy and high-speed position measurement, it is difficult to develop such environment usually. From the previous study, direct pointing visual feedback environment shows superior task performance than that of indirect pointing environment. However, our result means same task performances of the direct pointing environment can be realized with the indirect environment by adding haptic sensation.

When developing a lower DOF haptic device, the haptic rendering algorithm for compensating the decrement of DOF is required. Because 1 DOF mouse , which developed in this research, has only up-and-down haptic presentation function, some techniques are required. For example, as mentioned in this study, a gradually force increasing method to the user's finger to avoid unwanted vibration when presenting a wall of a large cube is required.

Moreover, when a user traces the surface of a quadrangular pyramid with the multiple DOF haptic device, the user can perceive the edge of the pyramid, because the reaction force vector is rapidly change on the edge. However, with 1 DOF device, it has ability to present the up-and-down direction only. When the user's finger overcomes an edge, the reaction force is not change hardly, since the device cannot present horizontal force vector. The user tend to feel a blur edge. In order to solve this, when a reaction force vector changes, increasing method of the feeling of an edge, such as adding vibration is required.

When building a direct pointing environment, it is necessary to implement high-speed and highly precise position detection for optimum fingertip operation. Since the infrared multi-touch overlay used in this research was insufficient in respect of speed, this issue was solved by using a set of optical sensors collectively. To build a direct pointing environment, it would be necessary to solve this problem, possibly by using multiple sensors.

As a result of the experiment, users can trace target positions in high accuracy in both pointing environments. As an application of the proposed system, the operativity of a GUI can be improved. In addition, our system can be applied to a computer aided surgery (CAS) and a surgical training system because the system has capability to present various shapes and elasticity of virtual organs.

There was a report of incongruity about equipment. Since the end effector is a plane attached to the linkage. It is inclined according to the finger's position even though the inclination of a touched surface is not changing. To solve this issue, it should be fabricated with a thimble and a gimbal which center is identical to the center of the fingertip. We plan to change the mechanism of the current end effector.

VII. CONCLUSION AND FUTURE WORK

In this research, we developed a prototype system, consisting of a 1 DOF mouse-like haptic device and a tabletop display with a multi-touch overlay sensor.

By actually constructing such a system including a haptic presentation device featuring a low DOF, the elements required to make the system functional were clarified.

Moreover, it was shown that the pointing environment does not contribute greatly to the performance in haptic presentations by measuring EMG etc.

As a haptic rendering technique, we proposed a virtual wall rendering method that is perpendicular to the ground. As one of other solutions is a method of using the 'visual dominance' in haptic presentation. We think it is possible to touch the vertical wall freely without sense of incongruity by presenting a steep slope as haptic sensation, and an image of the vertical wall as visual sensation simultaneously. We plan to develop such haptic rendering technique.

We also plan to use 'Pseudo-haptics' [9] with our system as a technique for increasing the capability of haptic expression. If a low DOF device is supplemented by visual information, the flexibility of the system can be extended to use with the pseudo haptics technique.

Moreover, although this current system only receives haptic presentation, we plan to improve the system so that a user can change the shape of virtual objects etc.

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