



Object Handling Precision Using Mouse-like Haptic Display Generating Tactile and Force Sensation

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Abstract- *This paper presents development of new haptic display capable of stimulating the muscles and tendons of the forearms as well as the tactile receptors in the fingers as a new approach for virtual reality device. Investigation of simultaneous presentation of both tactile and force effects are conducted and presented in this paper. The haptic display consists of a tactile display with a 4-by-12 array of stimulus pins driven by micro-actuators and an articulated manipulator. The display's handle was constructed replicating a conventional PC mouse so that anyone could comfortably use it without special training or operation knowledge. Vertical movement of the virtual tactile pad in the virtual world is controlled in proportion to the compressive force applied on the display pad. This makes it possible to reduce the operator's energy consumption during manipulation in 3D-space. Operators can now work in 3D-space in spite of their manipulations actually being done in 2.5D-space. Evaluation experiments were performed using the display, in both force-only mode and combined-mode (force +*

tactile) to verify its presentation capability. In the experiments, subjects tried to assemble virtual blocks in a line. Experimental results shows that the display combining tactile and force sensations provide higher accuracy in a precise virtual assembly task compared to the force-only display because the proposed display provides relative motion between the hands and the blocks.

Index terms: Haptic device, virtual reality, 2.5D-display, tactile sensation, objects handling.

I. INTRODUCTION

Our lifestyle has been drastically changed by the recent progress in electronic devices and products applying information technology (IT), such as personal computers (PCs) and smart phones. To manipulate these products, finding the ideal human-machine interfaces has become very important, and this importance increases when trying to support special group of people such as the elderly and disabled. The development of human-friendly interfaces within virtual reality (VR) environment is expected to meet the demands of these special groups for intuitive control based on the human senses. In addition, various VR applications such as rehabilitation [1-3] and tele-existence [4-5] require the capability to perform more accurate and realistic tasks.

For object manipulation in virtual space, the display device has become a key part for stimulating the human senses accurately [6-7]. A tactile and haptic presentation is effective because it involves the tactile sensation and reaction force caused by touching an object [8-9]. In particular, the tactile and haptic VR has two special advantages: first, users can experience a virtual sensation that is very similar to the real sensation caused by touching a real object; second, they can adjust the athletic load and select the type of exercise according to their intentions. Therefore, it is important to develop a new human-machine interface that can present tactile sensation and force, thus allowing us to perform advanced works and provide users with natural feelings. Since distributed pressure must be applied to human skin to stimulate a human tactile receptor, small actuators must be used to achieve high-density distributed arrays. In addition, a tactile display with large tactile surfaces having spatial resolution is needed for object recognition. However, it is very difficult to produce a composite presentation device combining tactile sensation and force since no tactile displays that capable of satisfying these requirements simultaneously has been developed for practical use, in spite of the many attempts [9-13].

In his paper, we presents development of new haptic display capable of stimulating the muscles and tendons of the forearms as well as the tactile receptors in the fingers as a new approach for virtual reality device. The haptic display consists of a tactile display with a 4-by-12 array of stimulus pins driven by micro-actuators and an articulated manipulator. The display's handle was constructed replicating a conventional PC mouse for ease in operation. Vertical movement of the virtual tactile pad in the virtual world is controlled in proportion to the compressive force applied on the display pad. This makes it possible to reduce the operator's energy consumption during manipulation in 3D-space. Operators can now work in 3D-space in spite of their manipulations actually being done in 2.5D-space.

II. MOTIVATION AND PRINCIPLES

In previous works [14-15], we have developed prototype haptic displays for tactile and force sensation. In one of the previous study, we have developed a matrix-type experimental tactile display for virtual reality systems [14]. However, this display could not present force sensation because it was not equipped with a manipulator. Based on current study, we developed a grip-type haptic device for peg-in-hole tasks, which was composed of a master hand with two sets of tactile displays [15]. We verified that a tactile-haptic display was effective for virtual peg-in-hole tasks in the case of relatively large clearance. Since we examined the effect of combined presentation in these experiments, the usage of the display was restricted to 2D-space. Although peg-in-hole tasks should essentially be done in 3D-space, the use in 2D-space has the advantage of not making operators tired during the task due to restriction of vertical movement. To keep this advantage on the one hand and to provide a virtual-object approach to 3D-space on the other hand, we introduce a new concept of virtual 2.5D-space. Here, we achieved a quasi-3D-space by adding to 2D-space the capability of vertical pointing controlled by compressive force. In the actual display, the compressive force is measured with a pressure sensor installed under the display pad of the actuator arrays. Thus, it is possible to reduce the energy consumption of operators during manipulation in 3D-space. Furthermore, we enlarged the size of the display pad to a 4-by-12 array of stimulus pins. Consequently, an operator can more naturally feel an object with three fingers than when using one finger with the previous displays.

The mouse has become a common conventional human-machine interface, and it has attracted the attention of several interesting researches [16-17]. Despite many attempts to use advanced mouse as part of commercial devices, the use is still limited to pointing devices for PCs. In addition, the commercial devices can only generate limited forces related to magnitude and direction. Therefore, we adopted a manipulator as the force display since a common mouse cannot present forces and moments to achieve virtual object manipulation. In the actual combined display, we created the handle of the display to be like a mouse. Since operators use it in just the same way as a real mouse, anyone can use it comfortably without special training or operator knowledge.

This study has two objectives: one is to develop a 2.5D-display generating combined tactile sensation and force; the other is to develop a presentation system to assist us in using this device in virtual space. Reaction forces are presented by the haptic device, while tactile information on the surface roughness of virtual objects is presented by the tactile display. In tests designed to evaluate our display device and its system software, we adopted handling of the virtual block as the task to verify the effectiveness of pressure and force presentation. This is motivated by daily-life tasks that require such basic operations as touch, grasp, move, and rotate, all of which are integral to the block assembly task. Furthermore, those basic operations are important for the applications of rehabilitation and tele-existence in virtual space.

III. HARDWARE STRUCTURE AND METHODOLOGY

a. Haptic display

We arranged a multi-modal display capable of stimulating the muscles and tendons of the forearms and tactile receptors in the fingers to investigate tactile and force effects during simultaneous presentation. Figures 1 and 2 show the haptic display and an overview of the system, which is composed of a planar manipulator used as a force display and a tactile display (Fig. 3) on the handle of the manipulator. Since we constructed the handle of the manipulator to be like a PC mouse, this display can be used by anyone comfortably. The controller is composed of a digital I/O board (PCI-2466C, Interface Inc.), an A/D and D/A converter board (PCI-3521, Interface Inc.), an encoder counter board (PCI-6205C, Interface Inc.), DC motor drivers (ADS 50/5, Maxon Motor Ag.), and a PC.

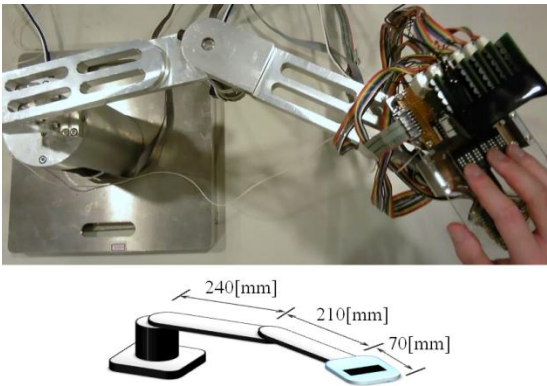


Figure 1. 2.5D-display generating combined tactile sensation and force

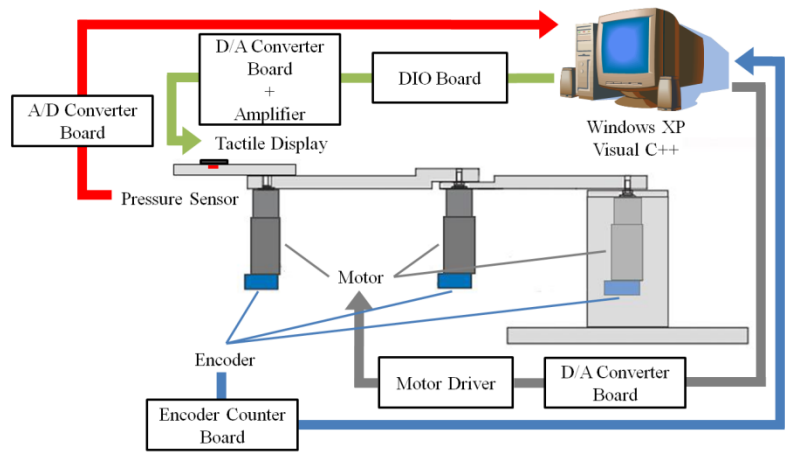


Figure 2. Schematic block diagram of compound display system

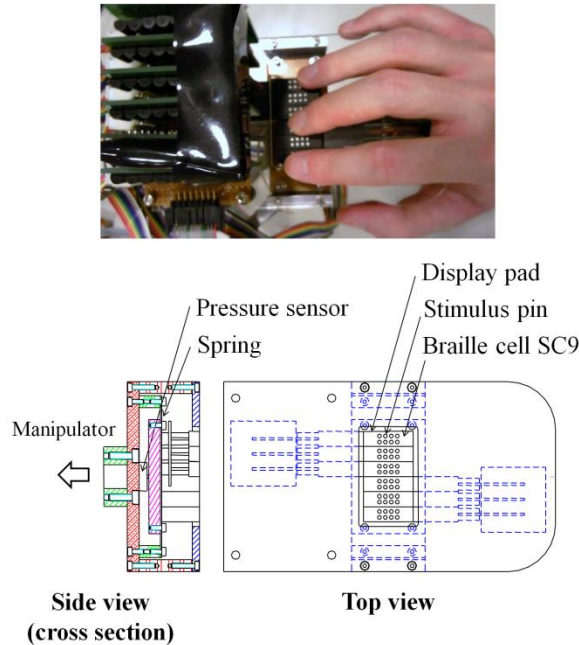


Figure 3. Tactile display

The haptic display is controlled by the following procedure. The joint angles of the manipulator are acquired by the pulse encoder mounted on each joint. Since the configuration of the manipulator is determined by the joint angles, the horizontal position information is calculated from kinematics. On the other hand, although the movement of the manipulator is planar, vertical movement of the virtual tactile pad in the virtual world is controlled by compressive force applied on the display pad. This compressive force is measured by a pressure sensor installed under the actuator array, so the vertical directional displacement can be determined based on compressive force. Therefore, we can use this device as a pointing device in 3D-space, despite the manipulations actually being done in 2.5D-space. Then, the contact interaction between the operator's fingertip and the virtual environment is calculated to obtain reaction force and distributed pressure. Joint torque and pressure-distribution signals, which are generated on each joint and the display pad, are sent to the motor drivers and a handmade piezoelectric actuator-driver (composed of D/A converter chips and charge-up transistors) through the A/D-and-D/A-board and the digital I/O board.

b. Force display

As the force display, a 3-link planar manipulator is used. The arm's first and second joints are driven by DC servo motors and pulse encoders (RE35, Maxon Motor Ag.), whose wattage and torque are 90 W and 1.4 N m. Since the lengths of the first and second links are 210 and 240 mm, the manipulator can generate maximum linear force of about 9 N at Joint 3, which functions as a wrist joint driven by a DC servo motor (RE25, Maxon Motor Ag.) of 25 W and 0.4 N m.

c. Tactile display

The tactile display is composed of piezoelectric bimorph ceramic actuators of a Braille cell (SC9, KGS, Co.) [18]. In the display, we used six Braille cells to make a 4-by-12 array of stimulus pins. Since we developed a handmade driver for the piezoelectric actuator, outputting analog voltage of 0 to 200 V, these stimulus pins are driven to generate intermediate values from 0 to 1 mm. The PC generates 8-bit digital signals corresponding to the ridge heights of the virtual textures. These digital signals are transmitted to the D/A converter chips and transformed to an analog signal of 0 to 5 V. Then, the transistors amplify them.

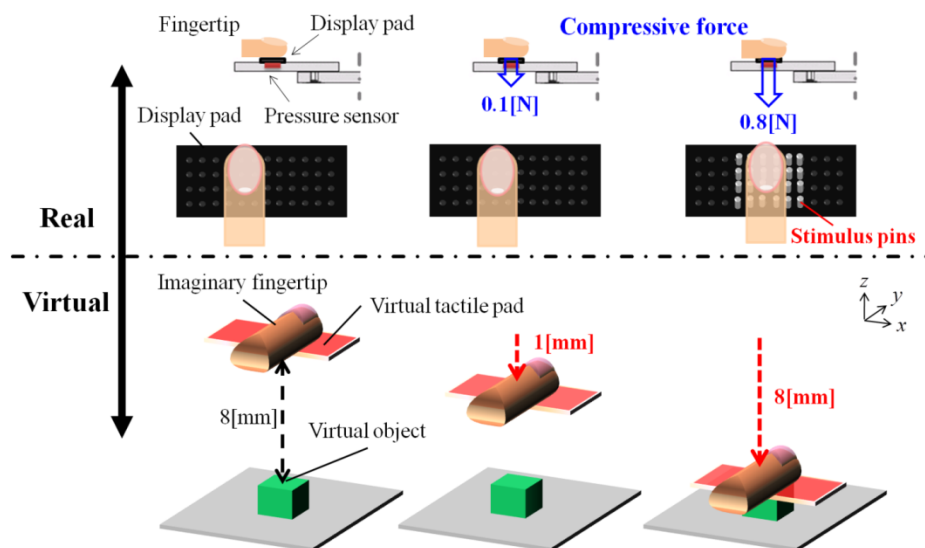


Figure 4. Altitude control

d. Altitude control

Haptic displays such as the PHANToM series [19] have become commercially available to meet the expected demands of manufacturing tasks such as those using CAD/CAM and remote operations. However, when operators work with the PHANToM series over a long time, they get tired because they have to maintain the same vertical movement in 3D-space. On the other hand, with pointing sticks such as TrackPoint (IBM Co.), the movement of the pointer on the screen is controlled by 2D-force applied through the operator's fingertip to the nonslip cap on the stick. Consequently, we adopted the function of TrackPoint for vertical pointing in our display and thus to move the virtual tactile pad in virtual 3D-space. This movement is controlled by compressive force applied on the display pad, which is measured by a pressure sensor installed under the actuator arrays. Consequently, operators can move the virtual tactile pad in virtual 3D-space in spite of their actual manipulations being done in 2.5D-space.

The vertical movement of the virtual tactile pad is determined by the following procedure depicted in Fig. 4. In the initial condition, the virtual tactile pad is placed in the air at a default distance apart from the virtual objects. The default position of the virtual tactile pad is 8 mm above the virtual objects, based on the assumption of minimum movement in the vertical direction. Operators can manipulate this display as if their fingertips were working through the tactile pad while placing their hand on the mouse, working as an end effector, as if they were using a hand rest. Thus, if they increase the contact force of the fingertips by shifting weight to

the fingertips, they can move the virtual tactile pad in the vertical direction. Accordingly, the vertical movement is controlled in proportion to the compressive force. Although we assume that the virtual tactile pad moves down 1 mm per 0.1 N in this paper, this force rate can be easily adjusted depending on the user's objective. Consequently, it is possible to reduce the operator's energy consumption during manipulation in 3D-space.

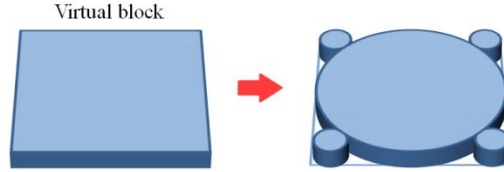


Figure 5. Approximation of virtual block

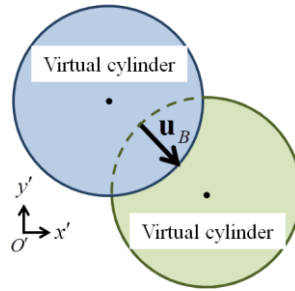


Figure 6. Contact between virtual cylinders

e. Estimation of contact force

In virtual space, forces and torques occur when the fingertip of the operator is in contact with virtual objects in the virtual environment. These virtual events caused by reaction can be obtained from the calculation of static and physical models. Therefore, we simplified the complicated contact problem between two elastic bodies. Also, we formulated two-dimensional equations based on the planar manipulator we employed.

We approximated virtual blocks with five virtual cylinders as shown in Fig. 5. Any contact between the cylinders is modeled as a point penetrating a cylinder, as shown in Fig. 6. The x - and y -directional reaction force $\mathbf{f}_B$ is calculated as

$$\mathbf{f}_B = K_B \mathbf{u}_B \quad (1)$$

where K_B is the spring constant of the virtual spring on the cylinder surface and $\mathbf{u}_B$ is the the x - and y -directional displacement caused by contact. Therefore, the reaction forces between the two blocks can be obtained based on Newton's law of action and reaction.

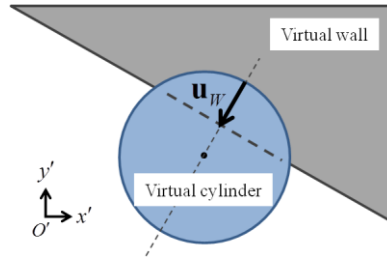


Figure 7. Contact between virtual cylinder and wall

On the other hand, we assumed that the virtual wall is comprised of straight segments. Any contact between the block and the wall is modeled as a point penetrating a segment, as depicted in Fig. 7. The x - and y -directional reaction force $\mathbf{f}_w$ is calculated as

$$\mathbf{f}_w = K_w \mathbf{u}_w \quad (2)$$

where K_w and $\mathbf{u}_w$ are the spring constant of the virtual spring on the wall surface and the x - and y -directional displacement caused by contact, respectively. In addition, viscous friction force acts between blocks and the virtual floor. Viscous forces are calculated by multiplying a coefficient of viscous friction μ and the velocity of the block. Thus, forces related to the i -th block $\mathbf{F}_i$ are obtained as

$$\mathbf{F}_i = \mathbf{f}_i - \mu \mathbf{v}_i \quad (3)$$

$i = 0, \dots, n$

where i , n , $\mathbf{f}_i$, and $\mathbf{v}_i$ are the number of the block, the total number of blocks, the sum of reaction forces from other virtual blocks and walls, and the velocity of the i -th block, respectively. According to the equation of motion, the acceleration of the block is calculated as

$$\mathbf{a}_i = \frac{\mathbf{F}_i}{m_i} \quad (4)$$

where m_i is the mass of the i -th block. Then, the positions of the blocks are determined by solving differential equations of Eq. (4) using the Runge-Kutta method.

f. Presentation method for force display

We adopted a three-link manipulator as the force display. Joint torques $\boldsymbol{\tau}$ to be generated are calculated by the manipulator's Jacobian matrix and the force-moment vector at the last joint $\mathbf{F}$. Based on robotic static analysis, the joint torques are given by

$$\boldsymbol{\tau} = \mathbf{J}^T \mathbf{F} \quad (5)$$

For the three-link articulated planar manipulator, $\boldsymbol{\tau}$ and $\mathbf{F}$ are 3x1 column vectors:

$$\boldsymbol{\tau} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{pmatrix}, \mathbf{F} = \begin{pmatrix} F_x \\ F_y \\ M_z \end{pmatrix} \quad (6)$$

where τ_1 , τ_2 , and τ_3 are the joint torques of Joints 1, 2, and 3, respectively. F_x , F_y , and M_z are the x- and y-directional force components and moment to be generated at the last Joint 3.

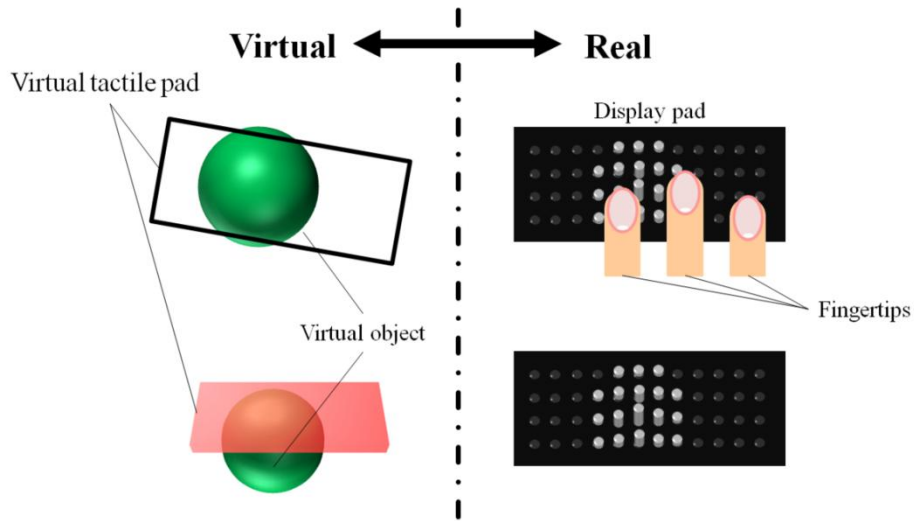


Figure 8. Surface of virtual objects

g. Presentation method for tactile display

Human operators touch the display pad with three fingers and manipulate it while maintaining contact between their fingers and the display pad. The tactile information on surface roughness of virtual objects is presented by the tactile display as shown in Fig. 8. In this way, operators can naturally feel virtual objects with three fingers. In the initial condition, the virtual tactile pad is placed in the air apart from the virtual objects in virtual space. When the virtual tactile pad contacts the virtual objects, operators can feel the object shape and the surface as a crown or hollow. The pin stroke is determined by the overlap of the virtual tactile pad with the virtual objects. Consequently, the operator can perceive the thickness of the virtual objects according to the change in pin protrusion.

h. Experimental procedure

In virtual reality device used for rehabilitation, the Simple Test for Evaluating Hand Function (STEF) is widely used to evaluate the motion function, especially quickness, of an upper limb [20]. In STEF, trainees repeatedly pick up and place objects in the appropriate positions. These tasks consist of basic operations such as touch, grasp, move, and rotate. Therefore, since these operations are essential for everyday life, we developed a presentation system (software) to assist us in these operations while using the proposed device in virtual space (Fig. 9). The simulation software is based on arranging the virtual blocks in a line. When virtual events occur in this system, reaction forces and surface unevenness of virtual objects are presented by the combined display. In this system, force and tactile sensations are presented according to the following procedure.

- i. The configuration of the manipulator is determined by the joint angle, and vertical movement is determined in proportion to the compression force.
- ii. The contact interaction between the fingertip of the operator and the virtual environment is calculated to obtain reaction force and distributed pressure.
- iii. The tactile information on surface unevenness of virtual objects is presented by the tactile display.
- iv. Before the operator grasps the virtual block, the manipulator motors' torques are not generated due to the force-free movement.
- v. After the operator grasps the virtual blocks by making contact with them using the virtual tactile pad, he or she sorts the virtual blocks along the wall. We adopted two conditions, 30 and 60 degrees, for the angles of the virtual walls.
- vi. If the block maintains contact with other blocks or the virtual wall, reaction force is calculated and presented by the haptic device.

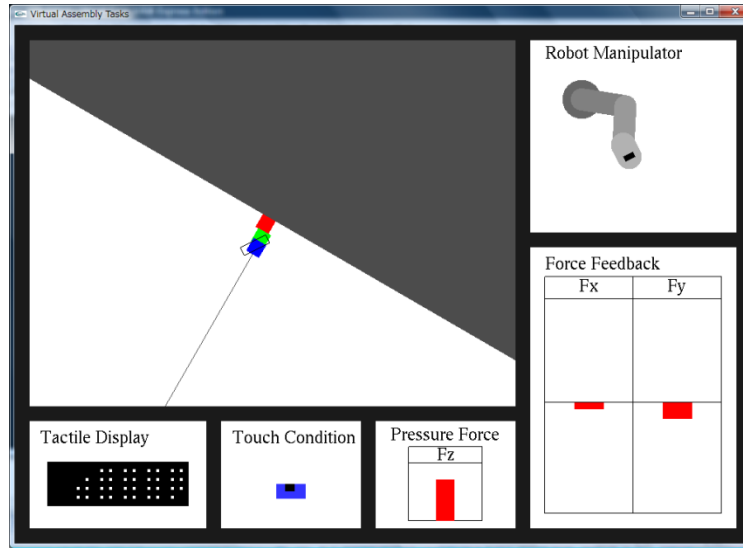


Figure 9. Virtual building tasks

To verify the effectiveness of this system and the proposed display, we performed a series of experiments with six human subjects (average age: 23.5, SD: 0.55), who sorted three virtual blocks to arrange them in a line. All persons were right-handed. In these experiments, we adopted the main parameters and constants shown in Table 1. The above procedure of Steps (1)–(6) was repeated 12 times for each subject. This procedure was performed under two conditions: 1) force only; 2) force and tactile reaction (combined mode).

Table 1: Main parameters and constants

Parameters and Constants	Value
Spring constant of virtual wall K_w	80 N mm ⁻¹
Spring constant of virtual blocks K_B	100 N mm ⁻¹
Width of virtual blocks	20 mm
Height of virtual blocks	20 mm
Depth of virtual blocks	2 mm

IV. RESULTS AND DISCUSSION

a. Evaluation method of error

To investigate the effectiveness of presentation based on pressure and force, the alignment precision was examined using the final configurations of three virtual blocks as the evaluation parameters. Figure 10 shows the scenario of these experiments. In these experiments, we measured the angular error and the positional error for each virtual block, depicted in Fig. 11. The positional errors of E_{D_1} , E_{D_2} , and E_{D_3} are defined as the distance between the virtual block's centroid and its centerline. On the other hand, the angular errors of E_{A_1} , E_{A_2} , and E_{A_3} are defined as the angle between the virtual block and the virtual wall. These angular errors are calculated as

$$\begin{aligned} E_{A_1} &= \alpha - \theta \\ E_{A_2} &= \beta - \alpha \\ E_{A_3} &= \gamma - \beta \end{aligned} \quad (7)$$

We used six males as human subjects (average age: 23.5, SD: 0.55). From each subject's results, we examined the effectiveness of the combined mode compared to the force-only mode using the above experimental criteria. Averages of experimental data for each subject are shown in Tables 2 through 7.

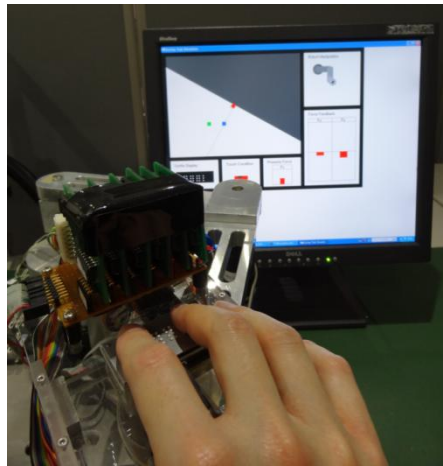


Figure 10. Scenario of experiments

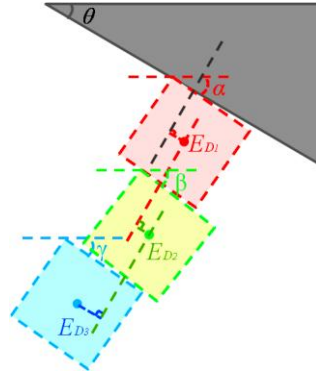


Figure 11. Definition of criteria

Table 2: Average of experimental data (subject A)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	5.04	1.90	1.00	1.75	0.91	1.25
	60	2.85	1.51	0.63	2.09	2.78	1.10
Combined mode	30	4.20	1.05	0.72	1.90	1.01	0.90
	60	2.53	1.31	1.44	1.21	1.10	0.90

Table 3: Average of experimental data (subject B)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	2.17	1.47	0.14	1.22	1.04	0.74
	60	1.00	2.53	2.48	1.99	0.98	1.14
Combined mode	30	2.61	1.49	1.15	1.38	0.83	0.55
	60	1.60	2.13	0.90	1.77	1.39	0.84

Table 4: Average of experimental data (subject C)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	1.62	1.13	0.81	0.74	0.66	0.93
	60	0.65	1.01	0.98	0.59	1.22	0.54
Combined mode	30	2.77	2.09	0.77	1.00	0.63	0.44
	60	1.29	2.10	0.66	0.80	0.23	0.75

Table 5: Average of experimental data (subject D)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	1.19	0.84	1.54	2.02	0.85	0.51
	60	2.51	0.99	0.91	1.20	0.46	0.56
Combined mode	30	1.79	1.70	1.27	1.57	0.44	0.14
	60	1.06	1.67	0.91	1.70	1.32	0.48

Table 6: Average of experimental data (subject E)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	6.17	1.71	6.45	3.08	1.24	1.59
	60	6.10	2.96	4.84	3.66	2.37	0.15
Combined mode	30	4.76	3.76	3.07	1.33	1.50	1.15
	60	1.32	2.12	4.19	2.31	0.88	0.97

Table 7: Average of experimental data (subject F)

	Wall [deg]	E_{A_1} [deg]	E_{A_2} [deg]	E_{A_3} [deg]	E_{D_1} [mm]	E_{D_2} [mm]	E_{D_3} [mm]
Force-only mode	30	4.57	1.66	3.81	2.17	1.65	2.50
	60	3.10	6.94	6.16	6.38	4.26	3.07
Combined mode	30	3.64	0.37	5.19	0.33	1.48	0.37
	60	4.13	4.80	5.83	1.44	2.24	2.31

b. Virtual wall angle of 30 degrees

First, we discuss the trials on the smaller wall angle because these tasks are relatively easy. From the experimental results shown in Tables 2 to 7, four criteria E_{A_1} , E_{A_2} , E_{A_3} , and E_{D_3} were reduced under tactile and force presentation (combined mode) compared to force-only mode for subject A. Similarly, four criteria E_{A_3} , E_{D_1} , E_{D_2} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject D. In addition, four criteria E_{A_1} , E_{A_3} , E_{D_1} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject E. Moreover, five criteria E_{A_1} , E_{A_2} , E_{D_1} , E_{D_2} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject F. Thus, the alignment precision for these subjects improved under the combined mode. These results show that, in particular, the angular adjustment is elevated for subject A and the positional adjustment is improved for subjects D, E, and F by using the combined mode. Therefore, the virtual building block task could be effectively completed under the combined mode for subjects A, D, E, and F when wall angle was 30 degrees. However, for subjects B and C, only three criteria E_{A_3} , E_{D_2} , and E_{D_3} were reduced under combined mode compared to force-only mode.

Next, the mean values and the standard deviations of all experimental results are summarized in Figs. 12–15. The results show that there are no major differences among all experimental criteria under force-only mode and combined mode. Since the wall angle was small, it seems that the

building tasks were carried out easily to obtain the above result. To examine whether a considerable difference exists between force-only mode and combined mode, we performed an F -test and a t -test (a two-sided test) under a 5% rejection rate as shown in Table 8. According to the F -test, there was no great difference between the variances of force-only mode and combined mode except for E_{A_2} ($F(17,17) = 0.366$, $P = 0.045 < 0.05$). Furthermore, there was a significant difference between the mean value of force-only mode and combined mode only for E_{D_3} corresponding to ($P = 0.024 < 0.05$). In addition, the standard deviations of E_{D_1} , E_{D_2} , and E_{D_3} showed almost the same value in combined mode as shown in Fig. 15. This result indicates that the order of building blocks does not affect the variances of the positional errors under combined mode.

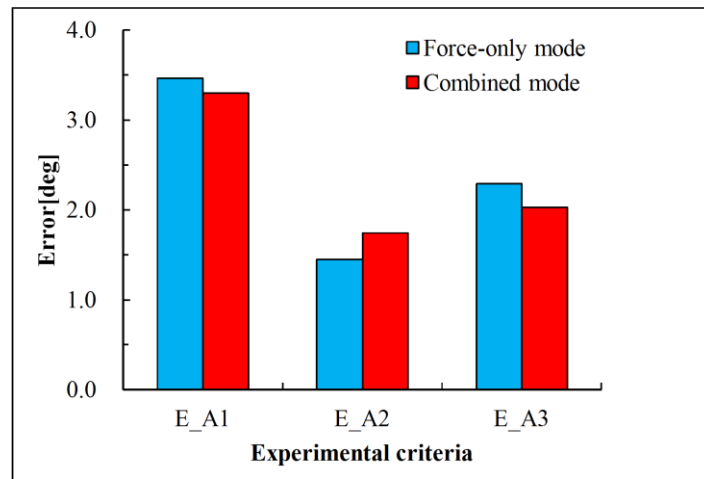


Figure 12. Average angular errors for all results (30[deg])

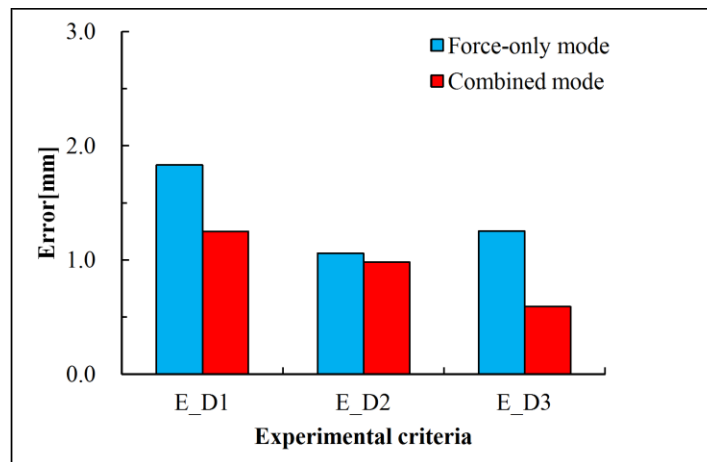


Figure 13. Average position errors for all results (30[deg])

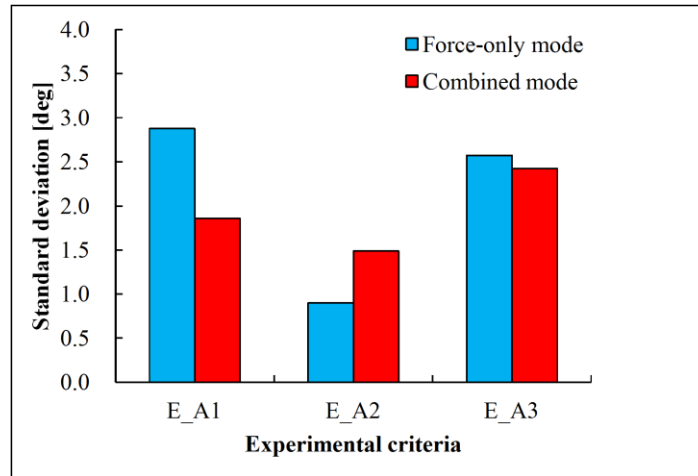


Figure 14. Standard deviation of angular errors for all results (30[deg])

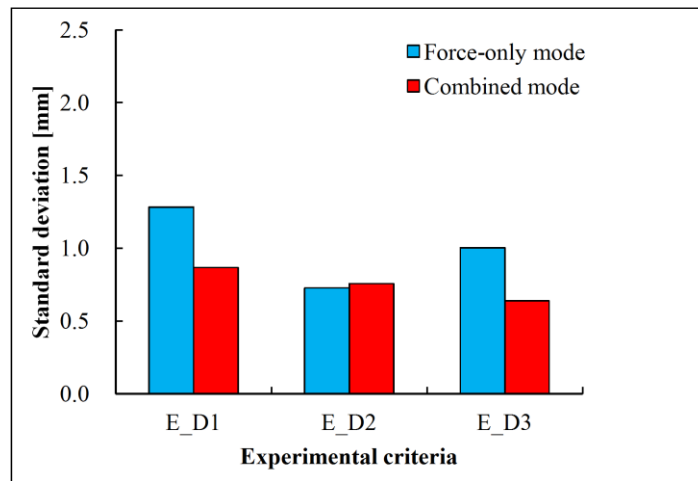


Figure 15. Standard deviation of position errors for all results (30[deg])

Table 8: *F*-test and *t*-test for experimental criteria (30[deg])

	<i>F</i> -test		<i>t</i> -test
	<i>F</i> (17,17)	<i>P</i> value	<i>P</i> value
E_{A_1} [deg]	2.397	0.080	0.837
E_{A_2} [deg]	0.366	0.045	0.484
E_{A_3} [deg]	1.126	0.810	0.754
E_{D_1} [mm]	2.185	0.117	0.120
E_{D_2} [mm]	0.923	0.871	0.760
E_{D_3} [mm]	2.472	0.070	0.024

c. Virtual wall angle of 60 degrees

Since the wall angle of 60 degrees is larger than that in the above case, the building tasks become more difficult. From experimental results shown in Tables 2 to 7, four criteria E_{A_2} , E_{A_3} , E_{D_1} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject B. In addition, five criteria E_{A_1} , E_{A_2} , E_{D_1} , E_{D_2} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject A. Similarly, five criteria E_{A_1} , E_{A_2} , E_{A_3} , E_{D_1} , and E_{D_2} were reduced under combined mode compared to force-only mode for subject E. Moreover, five criteria E_{A_2} , E_{A_3} , E_{D_1} , E_{D_2} , and E_{D_3} were reduced under combined mode compared to force-only mode for subject F. Thus, the alignment precision improved for all subjects under the combined mode. These results show that, in particular, the angular adjustment was elevated for subject E and the positional adjustment was improved for subjects A and F by using the combined mode. Consequently, the virtual building block task was effectively completed under combined mode for subjects A, B, E, and F when the wall angle was 60 degrees. However, two criteria E_{A_3} and E_{D_2} were reduced under combined mode compared to force-only mode for subject C. Similarly, two criteria E_{A_1} and E_{D_3} were reduced under combined mode compared to force-only mode for subject D. Therefore, the effectiveness of pressure and force presentation was not verified for subjects C and D because the alignment precision did not improve under combined mode.

We can verify the effectiveness of combined mode in five subjects (Subjects A, B, D, E, F) from these results. We assume that subject C gazed steadily at the screen during these experiments, since he depended more on visual information compared to other subjects. Thus, it seems that there was no major difference between the two conditions in his performance.

The mean values and standard deviations of all experimental results are depicted in Figs. 16–19. To examine whether a considerable difference exists between force-only mode and combined mode, we performed an F -test and a t -test under a 5% rejection rate as shown in Table 9. Although the mean values of all errors were reduced under the combined mode compared to the force-only mode, there is no major difference between force-only mode and combined mode according to the t -test. However, there are significant differences between the variances of force-only mode and combined mode in the positional error for E_{D_1} ($F(17,17) = 3.986$, $P = 0.007 <$

0.05) and E_{D_2} ($F(17,17) = 3.407$, $P = 0.016 < 0.05$). Although the visual information of the alignment position was not sufficient in this experiment, the variation of E_{D_1} decreased under the combined mode. Thus, subjects performed with stable operation to arrange blocks into the correct position under the combined mode. Since the blocks collided with each other frequently under the force-only mode, the position of the blocks gradually shifted.

On the other hand, under the combined mode, subjects could avoid collisions between the blocks because they perceived the position and attitude of blocks not only through reaction forces but also through tactile information. In addition, the standard deviation is the equivalent of the differential threshold (DL) in the realm of psychophysics. Therefore, the above results show that human subjects can recognize slight changes in alignment tasks under the combined mode due to the low thresholds.

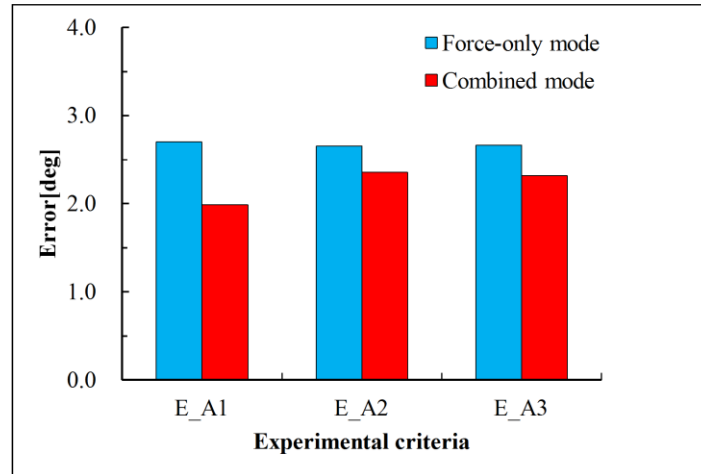


Figure 16. Average angular errors for all results (60[deg])

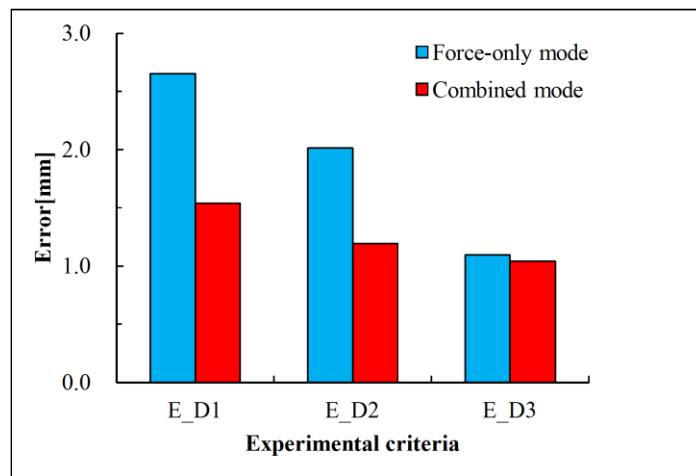


Figure 17. Average position errors for all results (60[deg])

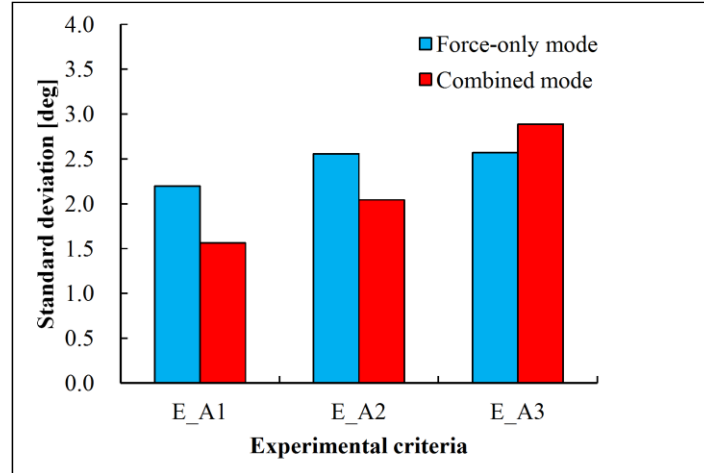


Figure 18. Standard deviation of angular errors for all results (60[deg])

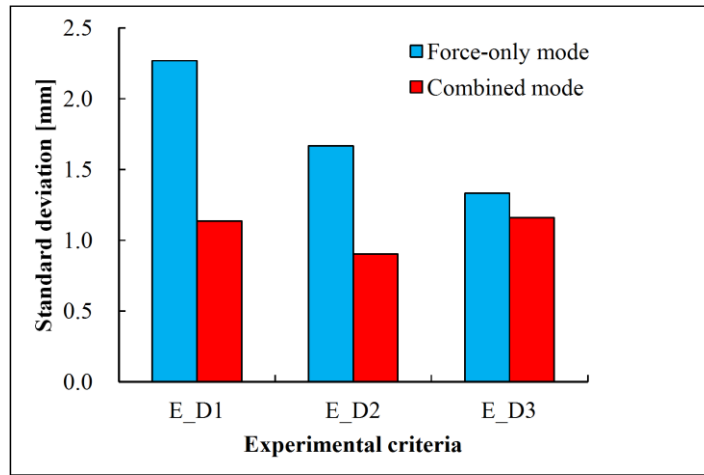


Figure 19. Standard deviation of position errors for all results (60[deg])

Table 9: *F*-test and *t*-test for experimental criteria (60[deg])

	<i>F</i> -test		<i>t</i> -test
	<i>F</i> (17,17)	<i>P</i> value	<i>P</i> value
E_{A_1} [deg]	1.977	0.170	0.270
E_{A_2} [deg]	1.567	0.363	0.698
E_{A_3} [deg]	0.791	0.634	0.708
E_{D_1} [mm]	3.986	0.007	0.075
E_{D_2} [mm]	3.407	0.016	0.078
E_{D_3} [mm]	1.320	0.574	0.898

These experiments (30 degrees and 60 degrees) were conducted in a situation with visibility. However, these tasks are impossible under force-only mode without visibility due to the lack of tactile sensation. Specifically, if these tasks were performed in a no-visibility situation, there would be greater differences between the two conditions than evidenced in these experimental results. We found some improvement in the tasks under the combined mode compared to the force-only mode in a situation with visibility. From our investigations, this display can be expected to reduce the burden on operators. Thus, this display can be applied to precise tasks such as computer aided design (CAD), since the alignment precision is improved while following the cursor on the screen. In such tasks, users can expect to perform stable operations.

V. CONCLUSION

We developed an advanced multi-modal 2.5D-display for tactile and force sensation. The proposed display has two main parts: 1) a master arm equipped with a tactile display using a 4-by-12 array of stimulus pins driven by micro-actuators and 2) an articulated manipulator functioning as a combined display for pressure and force presentation. Since the operator places three fingers on the tactile display, he/she can perceive the shape of an object in minute detail. In addition, we proposed a way of handling tasks in virtual 3D-space with horizontal movement based on compressive force (manipulations in 2.5D-space). In this method, vertical movement of the virtual tactile pad in the virtual world is controlled in proportion to the compressive force applied to the display pad, thus making it possible to reduce the operator's energy consumption during manipulation in 3D-space. Moreover, since the handle of the display functions in the same manner as a conventional PC mouse, anyone can use this display without special training or operator knowledge.

To verify the presentation capability of this display, we performed a series of experiments. In these experiments, six human subjects tried to arrange virtual blocks into a specific position to evaluate the alignment precision. The results show that alignment precision improved in most cases under the combined mode compared to the force-only mode, due to the significant differences between the two conditions. Since the relative position between the hands and the blocks cannot be acquired by a force-only display, precise assembly is impossible with the force-

only display. On the other hand, the assembly task can be completed using a combined display of both tactile and force sensations.

In future work, we will extend the versatility of operation in 2.5D space for object manipulation in 3D space. Since the surface rotation of the virtual tactile pad was limited to the z -axis, the contact region during object exploration was restricted within a plane. In order to express the rotations around the x - and y -axes, we propose using the moments around the x - and y -axes instead of rotations. In addition, we will apply the proposed display and system to the realm of rehabilitation. There is every reason to expect that object handling with this approach would be effective for patients recovering the function of their hands. In particular, we will develop the proposed display and system for use with a method of presenting vibratory stimulus synchronized with the movement of the hands, which is expected to promote effective training [21]. Furthermore, we will conduct a series of psychophysical experiments to examine how an operator feels during the task.

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