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Full paper

A haptic representation system for a virtual plain wall

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Abstract—The purpose of this study is to develop a virtual wall display system for a walk simulator to grope its way in an 'invisible' situation, such as in a building filled with dense smoke, etc. To reproduce the realistic haptic sense of a building wall, the implementation of the wideness and the rigidity of wall are essential. Wideness of a virtual wall was realized by a hand-tracking control combined with a small wall panel which is mounted on a three-axis Cartesian manipulator. A 6-d.o.f. magnetic tracking system was utilized for the hand position tracking in the non-contact situation of the hand and the panel. In the contact situation, high rigidity of the wall was attained as stiffness in the normal direction is provided to the wall panel to represent the haptic sense of a rigid wall. Force-based tracking provides the low stiffness in the tangential direction to make the wall panel move easily along the direction of hand movement to represent a wide plain wall. A three-axis force sensor is attached on the wall panel to detect the contact force. The realization of smooth switching between both tracking controls provides the user with the haptic feel of the presence and continuity of a virtual wall. In addition, the frictional sensation has the effect of giving the system more reality. Experimental results have shown the effectiveness of the hybrid tracking method for the virtual wall system.

Keywords: Virtual wall; haptic display; encountered type; hybrid tracking.

1. INTRODUCTION

In daily life, it is important to escape safely from buildings in cases where, for example, the visibility is extremely limited due to dense smoke from a building fire, electricity failure at night, etc. Fire escape exercises are sometimes performed to prepare for such emergencies, but it is inconvenient to prepare such an 'invisible' situation on the human scale by using actual buildings or mockup models. Therefore, utilization of virtual reality (VR) technology for the escape simulator is expected to be effective, e.g. for studies of escape behavior, escape time estimation, etc. Some systems for fire simulation have been proposed [1, 2] and, in particular, a VR fire simulation system [2] is able to generate a graphic rendering of fire and

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smoke, and even the thermal sense of fire. However, most of the systems (including this system) are non-experience-type systems — the users are not allowed to experience the simulated environment. Hence, a fire simulator that provides interaction between the users and the simulated environment is needed.

In a situation without visual information, a person will rely mainly on the proximity sensation of physical contact, primarily with walls together with some other solid plane surfaces of cabinets, furniture, etc. Thus, to seek an escape route, the most fundamental and expected behavior is to grope and recognize the way by the haptic feedback sensation obtained from the hands and other parts of the body. Therefore, the haptic representation of the simulated environment is most important to a VR fire escape system and a fire simulator with a haptic representation that allows user to perform the groping motions is required.

For the haptic representation of a virtual wall, it is necessary to provide the user with a clear haptic difference between the contact and non-contact situation. Various types of haptic devices have been developed, e.g. PHANToM [3, 4], CyberGrasp [5], SPIDAR [6], HapticGEAR [7], Rutgers Master [8] and MasterArm [9]. However, those haptic devices are of the immersive or grasp types that must be held or worn by the user and, thus, it is difficult to provide a real non-contact sensation to the user. On the other hand, McNeely [10] proposed an encountered-type haptic device that has the performance to realize real contact and non-contact situations. The user does not need to hold the device all the time; instead, the system tracks the hand motion and allocates the haptic device at an appropriate position for the encounter of the hand. Several sets of research on the use of the encountered-type haptic device have been proposed, e.g. Hirota and Hirose [11] and Tachi *et al.* [12] proposed the method of a curved surface display of a virtual object, Yoshikawa *et al.* [13] proposed a touch/force display system with the utilization of a optical fiber on/off sensor for the detection of a finger position, and Yokokohji [14] developed the WYSIWYF system: visual/haptic interface system. Furthermore, in several works a haptic interface of the 'virtual wall' has been proposed [15–17]. Lawrence *et al.* [15] introduced performance metrics for hard virtual surfaces which have clear relevance to human perception of hardness. Salcudean [16] used a braking pulse to make surfaces quickly damp out a motion and, thus, appear stiffer. Colgate *et al.* [17] provided a theoretical analysis and the criterion of the passivity for the implementation of a stiff wall. However, these works on virtual wall haptic display have mainly been intended to generate only the infinite stiffness of the virtual wall in the pushing direction. However, the continuous wideness along the wall has not been considered yet as another essential factor in the implementation of the virtual wall.

In this paper, we propose a virtual wall display system using an encountered-type haptic device and a hand-tracking control method to realize a haptic representation of a virtual plain wall. It is also intended to realize a virtual continuous and wide plane wall for a groping motion by using a limited size plane panel. Smooth motion switching between both the contact and non-contact situation has been implemented to provide the feel of virtual wall continuity to the user.

2. CONCEPT AND DESIGN OF A VIRTUAL WALL

To investigate and develop a virtual wall system for a walk escape simulator, three steps (i.e. requirements, conceptual design and system configuration for implementation) have been sequentially analyzed (Fig. 1). The main points in each step are detailed below.

2.1. Requirements of a virtual wall

To construct a virtual wall system, a haptic device is first required from the viewpoint of the two fundamental essential specifications of both force feedback and material properties feeling. The force feedback specifications are categorized by normal and tangential components on the wall surface caused by the hand motion. Another function is to represent a continuously wide and plain wall with the necessary area like an actual wall. As a panel with a limited area would be inevitably used as a virtual wall with haptic sense, some control method to deal with this function will be required. The requirements of a virtual wall are illustrated in the left items of Fig. 1 as:

(i) Stiffness against the normal force: the basic property of the wall is definitely strong; therefore, the wall position needs to be constrained against the pushing force of the user's hand.

(ii) Continuous surface: the virtual wall must also provide the user with the wide area sensation of a wall in the tangential direction of motion.

(iii) Representations of material properties such as friction and texture sensations at the hand are important to give the system more reality.

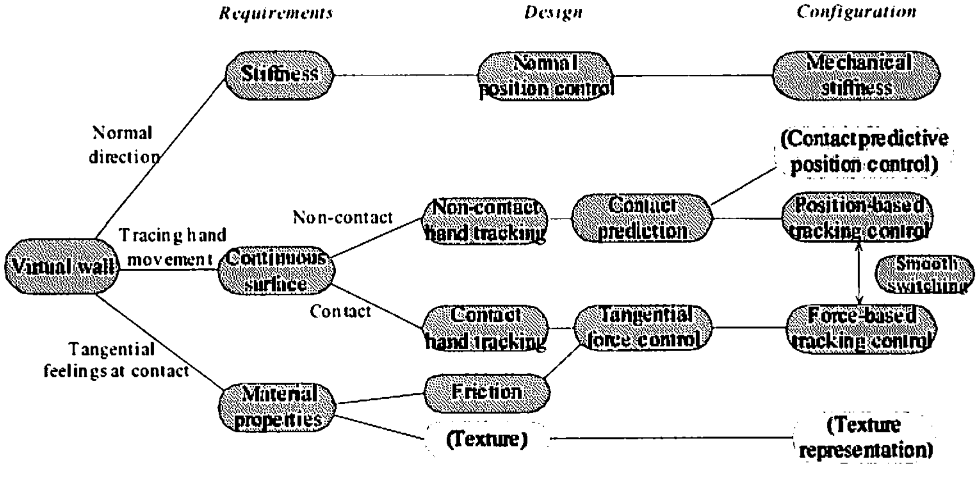

Figure 1. Structure of the virtual wall system showing the process from requirements to configuration.

2.2. Conceptual design

To achieve the requirements of the virtual wall, the system has been designed as follows:

(i) To represent a stiff wall against the pushing force, the displacement of the wall panel in the normal direction should be compensated for at any contact condition of the hand. The position control is commonly used to constrain the normal position and provide the stiffness to the wall panel.

(ii) The continuous surface of the virtual wall is realized by the use of a small wall panel instead of a large-scale virtual wall device. The hand-tracking control of a small wall panel is investigated to enlarge the scale of the virtual wall. The tracking system is required to track the user's hand in both the contact and non-contact situations. In the non-contact situation, contact prediction of the user's hand is required to move the wall panel to the predicted contact position. However, force control is applied to reduce the stiffness of the wall panel in the tangential direction for light tracking in the contact situation.

(iii) For the representation of material properties, the surface frictional sensation is picked up by adding the frictional force to the force control. As haptic texture representation [18] is an independently big problem, it is left to future investigation.

2.3. System configuration of a virtual wall system

To implement the virtual wall, the important factors of the system could be configured as shown in the right columns in Fig. 1:

(i) The use of only position feedback control along the normal direction of the wall surface inevitably gives the feeling of the compliance of the direction. To realize a very high stiffness along the normal direction (a) the parameters of the position feedback control are tuned to realize both the high stiffness and high speed responses actively, and furthermore (b) ball-screw mechanisms are adopted on the axes of the manipulator to constrain the wall panel position passively against the pushing force from the user's hand.

(ii) For the hand-tracking control of the wall panel, in both the non-contact and contact situations, two kinds of controllers are utilized. In the non-contact situation, the wall panel is to be positioned at the predicted hand-and-wall contact point, and thus position-based control is utilized. In the contact situation, the user's hand is necessarily stuck on the wall panel because actual hand slip will cause the hand to leave the panel. Therefore, slipping of the hand on the wall is substitutionally represented by the hand tracking without slip and the tangential force control. This means that the dynamic frictional force in the virtual space is substituted by the static frictional force in the real space.

(iii) Switching from position-based control to force-based control immediately after the contact causes motion discontinuity due to the sudden deceleration of the wall panel motion, since the force-based control gives a small initial output. That will cause some problems, such as the hand leaving the panel and the sense incongruity due to an error of the represented frictional coefficient of the virtual wall that is caused by an instantaneous large contact force. In order to solve these problems, smooth switching by a hybrid control method where the control mode is gradually changed is applied to maintain the smooth motion in order to give a natural feeling of a continuous virtual wall during groping. During the contact, the control mode will be finally completely switched to the force-based one.

3. SYSTEM OUTLINE OF A VIRTUAL WALL SYSTEM

3.1. Hardware configuration

To realize the virtual wall specifications as mentioned above, the system apparatus was constructed of four main components as follows:

(i) Hand position sensor part: the 6-d.o.f. magnetic position sensor [19] is used to detect the user's hand position in the non-contact situation. The sensor receiver is mounted on the palm of the hand in order to allocate the position.

(ii) Force detection part: the three- and one-axis force sensors are structured in the wall panel and cooperatively detect the three-direction contact force.

(iii) Manipulator part: an AC motor drives the three-axis Cartesian manipulator with a speed servo-controller helping providing the free motion of the wall panel for the hand tracking and the allocation of the virtual wall position. The speed servo-controllers receive a speed command from the system control part and take charge of automatic processing of the motor speed control. The motion activation of each axes of manipulator is performed by the driving control of the ball-screws.

(iv) System control part: this takes charge of sensor information processing and the manipulator system controller. The control system manipulates the wall panel by activating the three axes of the manipulator. The system control part is configured by two PCs, and is connected *via* an Ethernet to distribute the processing loads of manipulator control and sensor processing.

3.2. Wall panel and force sensing structure

The wall panel serves as a virtual wall display part and a contact force sensing part. Figure 3 shows the structure of the wall panel. The wall panel was built using the specifications defined below:

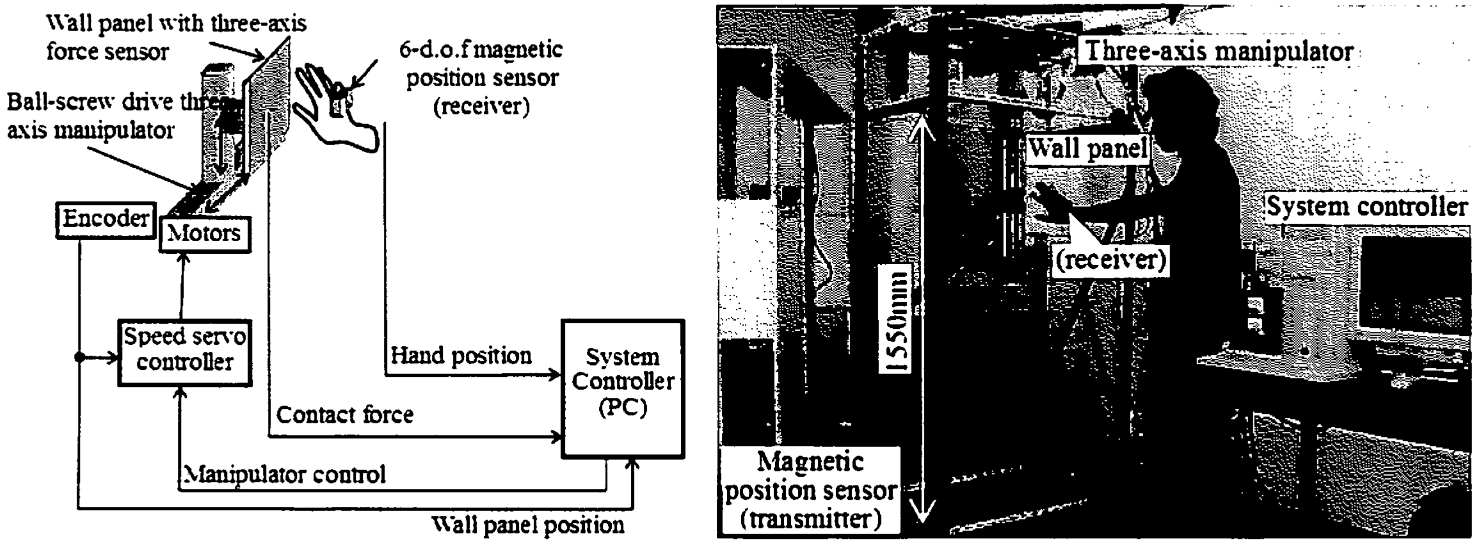

Figure 2. The entire configuration of a virtual wall system.

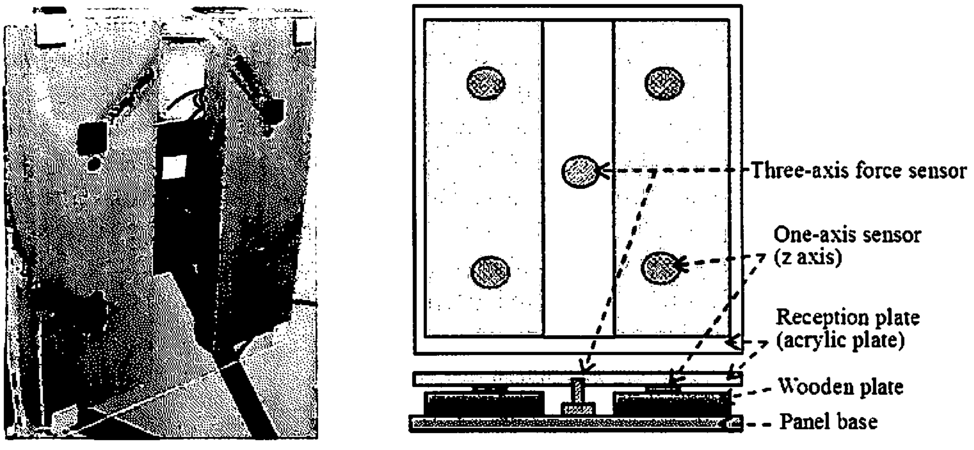

Figure 3. The structure of the wall panel device.

(i) An acrylic plate (200 mm height × 280 mm width) is set at the panel front part as a force reception part for hand contact and simultaneously represents the haptic display of the virtual plain wall.

(ii) The wall panel is mostly made from non-metallic material in order to reduce the influence on the magnetic position sensor.

(iii) The wall panel is structured with a three-axis force sensor (NITTA Pico-Force™) and one-axis force sensors (Tekscan Flexiforce™). One three-axis force sensor mounted at the center of the panel is used to detect the contact force of the user's hand that is exerted on the whole panel. However, the normal force away from the center gives the bending moment to the three-axis force sensor and as the result causes non-negligible errors of the tangential forces. In order to reduce this error, the one-axis force sensors are equipped into the force detection structure of the wall panel as shown in Fig. 3. Four one-axis force sensors are allocated at four corners around the wall panel and support the reception plate. Using this structure, the normal force away from the three-axis force sensor will mainly be applied to these one-axis force sensors and the pseudo-tangential force due to the bending moment is reduced. These one-axis force sensors are set free to the sliding motion of the reception plate in order to avoid the tangential force components. The three-axis contact forces $f_{x\mathrm{p}}$, $f_{y\mathrm{p}}$ (tangential forces) and $f_{z\mathrm{p}}$ (normal force) are derived as follows:

$$
\begin{aligned}
f_{x\mathrm{p}} &= f_{3x},\\
f_{y\mathrm{p}} &= f_{3y},\\
f_{z\mathrm{p}} &= f_{3z} + f_{11} + f_{12} + f_{13} + f_{14},
\end{aligned}
\tag{1}
$$

where $f_{3(x,y,z)}$ and $f_{1(1-4)}$ are the outputs of three-axis and one-axis force sensors, respectively.

(iv) The pseudo-tangential force due to the normal force of 10 N applied on the panel is less than 0.8 N, and especially less than 0.4 N when the normal force is applied within 100 mm from the three-axis force sensor. This bending moment will not affect the tangential force detection when the hand contact point is close to the three-axis force sensor. Furthermore, setting of the frictional coefficient also helps avoid this problem when the ratio of the normal force is larger than the pseudo-tangential force. The calibration of the force sensors has been performed experimentally by giving forces to the wall panel, since the detection of normal force on the reception plate has fluctuates in sensitivity due to the setup of the four one-axis force sensors.

4. CONTROL SYSTEM

4.1. Overall system

The conceptual diagram of the overall system is shown in Fig. 4. The system is essentially a hybrid control system integrated with position-based tracking and a force-based tracking. In the non-contact situation, only the position-based tracking controls the wall panel to track the hand position in order to keep the wall panel close to the hand. In the contact situation, the force sensors feedback a tangential force to realize smooth force tracking and also feedback a normal force to generate the frictional force. The switching process integrates the outputs from both tracking controllers and decides the state of the wall panel motion according to the contact condition of the hand and the wall panel.

4.2. Virtual wall and manipulator coordinates

To describe the motion of the virtual wall system, two coordinate systems, i.e. a world coordinate system and a virtual wall one, are set as shown in Fig. 5. The Cartesian world coordinate system $X_wY_wZ_w$ as the world coordinate system is attached to the base of the manipulator and the virtual wall XYZ of a simulated environment. The Y-axis on the wall panel is collinear to the Y_w-axis and the X-axis makes an angle θ against the X_w axis, the wall panel being rotated around the Y-axis. The wall panel moves along the direction of the virtual wall region in order to display a wide plain wall. When the three-dimensional position of the origin of the virtual wall is $\boldsymbol{p}_w$, the user hand $\boldsymbol{p}_h$ from magnetic sensor and the wall panel $\boldsymbol{p}_p$ from encoder, the hand and wall panel position in the virtual wall coordinate system are expressed as $\boldsymbol{p}_h - \boldsymbol{p}_w$ and $\boldsymbol{p}_p - \boldsymbol{p}_w$, respectively.

4.3. Detection of hand contact

The contact detection rule was implemented by using of the outputs from both the position and force sensors. Contact detection based on the contact force may cause

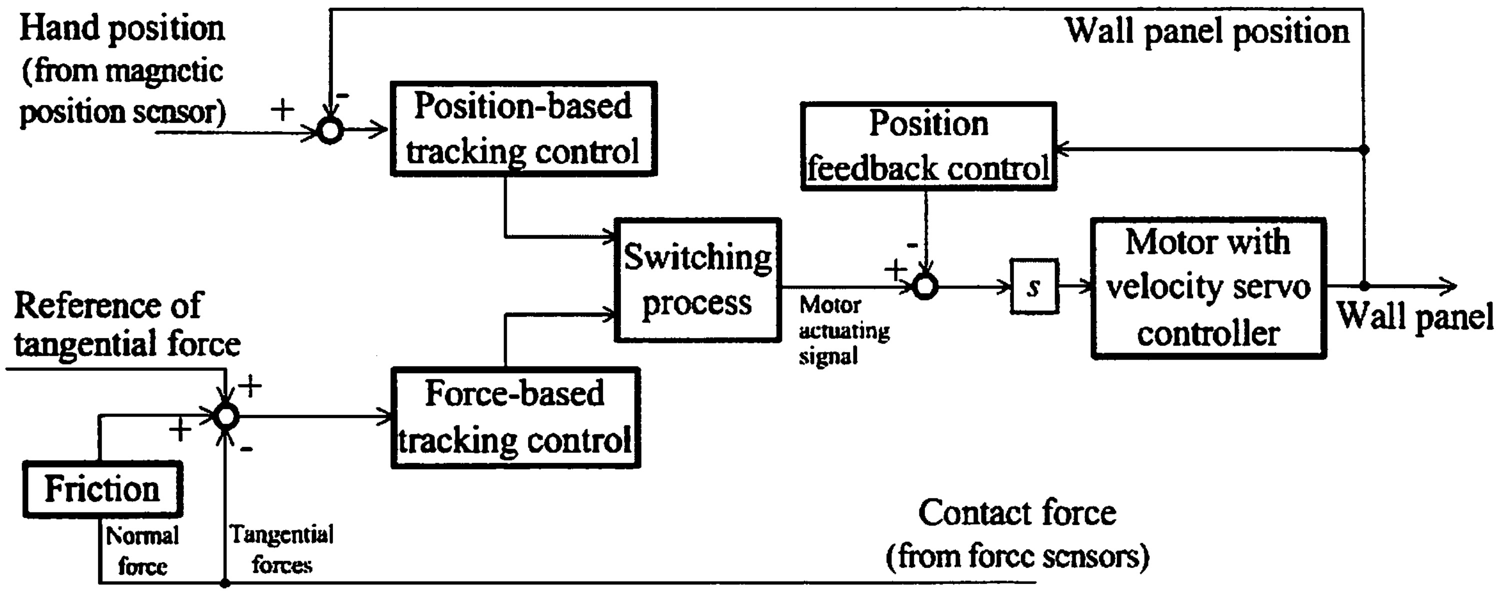

Figure 4. Conceptual diagram of the overall control system.

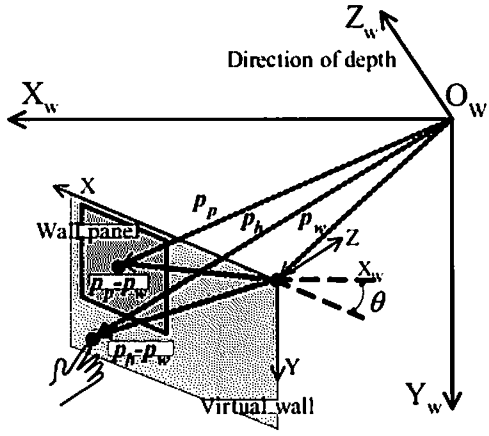

Figure 5. Coordinate systems for the world and wall panel.

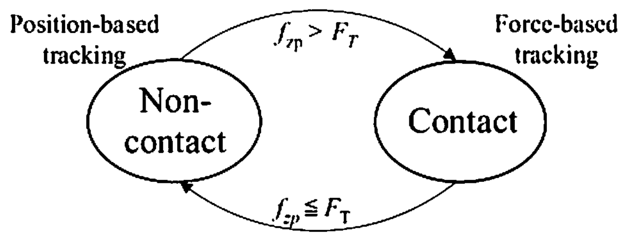

Figure 6. State transition diagram.

a false detection because of the mechanical vibration of the manipulator. Hence, position tolerances to estimate the hand contact were introduced as:

$$z_p - z < D_h \text{ and } (x_p - x)^2 + (y_p - y)^2 < D_t^2, \tag{2}$$

where x, y and z show a wall panel position, x_p, y_p and z_p are hand positions, and D_h and D_t are constants representing the tolerance distances in the normal and tangential directions of the wall. D_h and D_t have been determined experimentally as 80 and 100 mm, respectively.

The contact detection rule using the contact force is determined by:

$$f_{zp} > F_T, \tag{3}$$

where f_{zp} is a pushing force and F_T is the contact threshold level. F_T was experimentally set as 0.8 N based on the noise level of the force sensor. When both conditions (2) and (3) are satisfied, the hand is regarded to be in contact with the panel. Figure 6 depicts the state transition of contact and non-contact situations.

4.4. Hybrid tracking control system

4.4.1. Entire tracking control. An overall position/force-based tracking control system is illustrated in Fig. 7. The position tracking in the upper part of Fig. 7

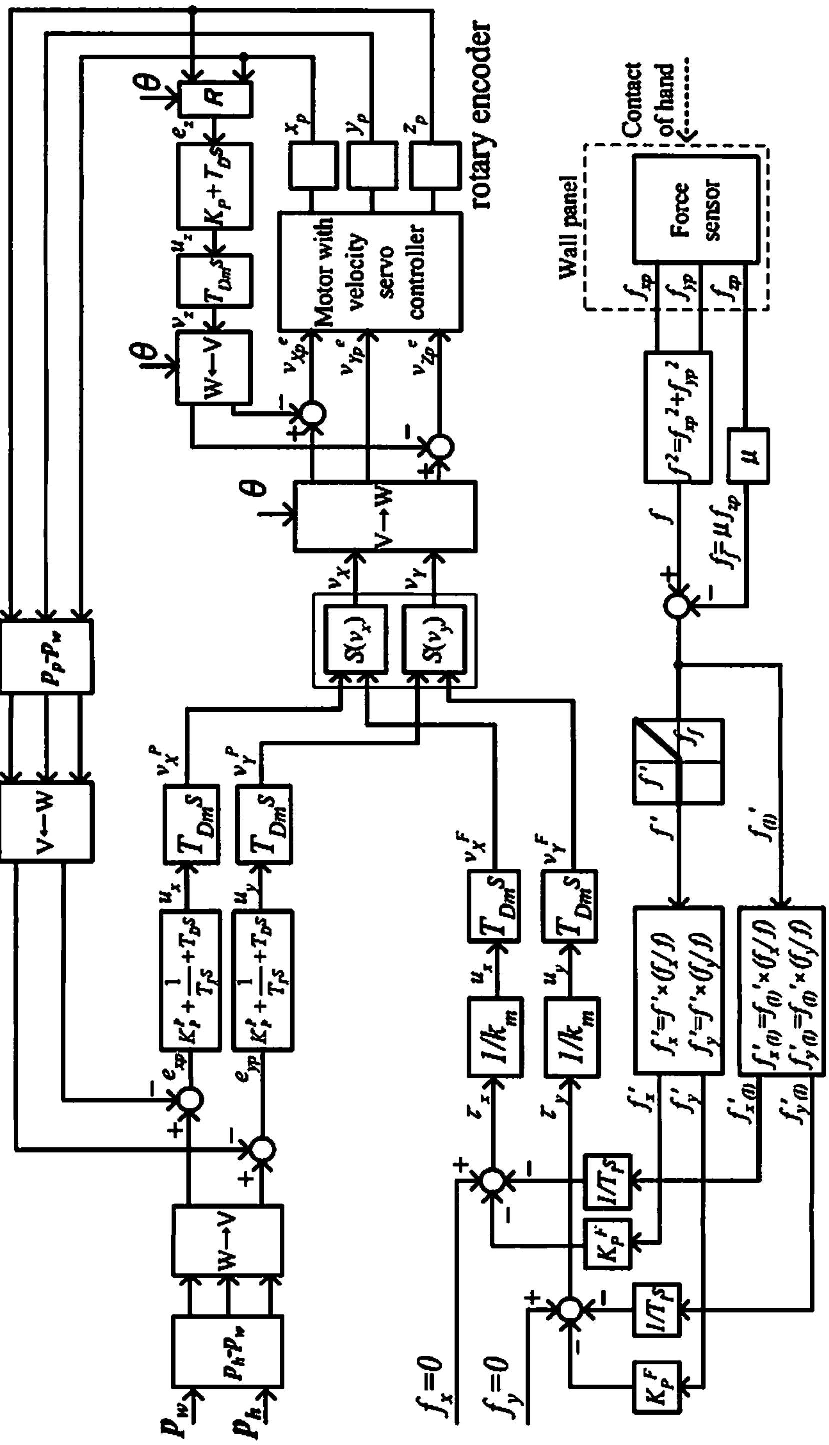

Figure 7. Total block diagram of tracking control: W = world coordinates; V = virtual coordinates.

is set as the reference value at the hand position. The reference position and feedback position of the world coordinate system are transformed into the virtual wall coordinate system (W → V) during the control process and transformed back to the manipulator (world) coordinate system (V → W) at the output process as:

$$\mathrm{W} \rightarrow \mathrm{V}: \begin{aligned} b_x &= \sqrt{a_x^2 + a_z^2} \\ b_y &= a_y \end{aligned} \qquad \mathrm{V} \rightarrow \mathrm{W}: \begin{aligned} a_x &= b_x \cos\theta \\ a_y &= b_y \\ a_z &= b_x \sin\theta, \end{aligned} \tag{4}$$

where $\boldsymbol{a}(a_x, a_y, a_z)^{\mathrm{T}}$ and $\boldsymbol{b}(b_x, b_y)^{\mathrm{T}}$ are the vectors in the virtual wall and the world coordinate system, respectively.

The force-based tracking in the lower part of Fig. 7 is set as the reference value of the frictional force and completes the close-loop control by the feedback of the contact force from the force sensors. In the system, the outputs of both controllers are used to generate the velocity command components (v_x and v_y) along the wall panel. $S(v)$ is a switching function to generate the actuating signal from both controllers. In the main loop of the control system, the PD feedback control corrects the wall panel normal position together with the tangential tracking motion.

4.4.2. Control algorithm for non-contact tracking. In the non-contact situation, the position-based tracking controls the wall panel to track the hand position in real-time during which the hand is away from the wall panel for the virtual wall in order to keep the wall panel position near the hand position.

PID feedback control is applied to the position-based tracking. The wall panel moves in the X- and Y-axes of the virtual wall coordinates to track the desired position that is set at the nearest distance between the user hand and the wall panel.

4.4.3. Control algorithm for contact tracking. In the case of contact tracking, position-based tracking is ineffective due to the mechanical impedance of the overall control system. Hence, force-based tracking is applied to reduce the load along the tangential direction by giving a reference force for the force controller by the value zero. Thus, the wall panel moves easily along the direction of the hand movement. In addition, generation of surface property sensations due to friction enhances the feel of tracing the wall.

4.4.3.1. Force applied to the virtual wall. There are two kinds of contact behaviors that the user gives to the wall panel in accordance with the direction of the force, i.e. pushing and tracing behaviors. Contact behavior is defined by the comparison of the tangential force defined in (5) and the frictional force in (6):

$$f^2 = f_{x\mathrm{p}}^2 + f_{y\mathrm{p}}^2, \tag{5}$$

$$f_{\mathrm{f}} = \mu f_{z\mathrm{p}}, \tag{6}$$

where $f_{x\mathrm{p}}$ and $f_{y\mathrm{p}}$ are tangential forces, $f_{z\mathrm{p}}$ is a normal force and μ is a frictional coefficient.

The frictional force works constantly in the opposite direction to the tangential force and is proportional to the normal force. A tracing behavior occurrs when $f \geqslant f_f$ and a pushing behavior occurs when $f < f_f$. A variable f' in (7) is the effective tangential force:

$$\begin{array}{ll} f' = f - f_f & (f \geqslant f_f) \text{ or} \\ f' = 0 & (f < f_f). \end{array} \tag{7}$$

For pushing behavior ($f < f_f$), the wall panel tangential motion is steady in a non-tracking motion and a tracking motion starts when the contact state changes to the tracing behavior ($f \geqslant f_f$).

4.4.3.2. Force tracking algorithm. Force-based tracking is implemented by giving a designed force of the PI compensator to the frictional force. The wall panel has to continue to move without any unnatural speed change just after a hand begins to trace the wall panel. At the same time, the wall surface frictional sensation is generated to the user's hand when the tangential force level approaches the designed frictional force.

4.4.4. Stiffness representation and wall position correction. To present a stiff virtual wall in the normal direction, the normal position of the wall panel has to be constrained against the normal force in any contact condition. To avoid any unnatural feeling caused through the repelling reaction of the wall panel by the dynamics of the feedback control system, a ball-screw mechanism has been adopted.

4.4.5. Switching process. The contact and non-contact switching frequently occurs when we grope a real wall. In general, two types of contact action to a wall can be noticed, i.e. contact and go (C-Go) (a sequential action as non-contact–push–pulled off) and contact and trace (C-Tr) (a sequential action as non-contact–contact–trace). In the case of C-Go, when the wall panel is pushed, the frictional force is larger than the tangential force; therefore, the wall panel is changed to the pushing state with non-tracking motion. In the case of C-Tr, the feeling of motion discontinuity through the hand contact has to be prevented. Therefore, a method for the smooth change from non-contact to contact tracking has to be devised.

The idea of the switching process is to maintain the speed of the wall panel while the user's hand is moving from the non-contact to contact situation. The empirical percentage of motion speed change that gives the user a continuous motion sensation should be below 15% of the moving speed. Therefore, the switching process is implemented by smoothing the changing of velocity command v from v^P to v^F as given in (8) so as to interpolate these two values. The concept of the motion switching process is depicted in Fig. 8. Setting of the velocity command for motion switching allows the control mode to change gradually with increasing output from the force controller as given in (9). The switching period starts when the user's hand contacts with the wall panel and the control is completely switched to the force

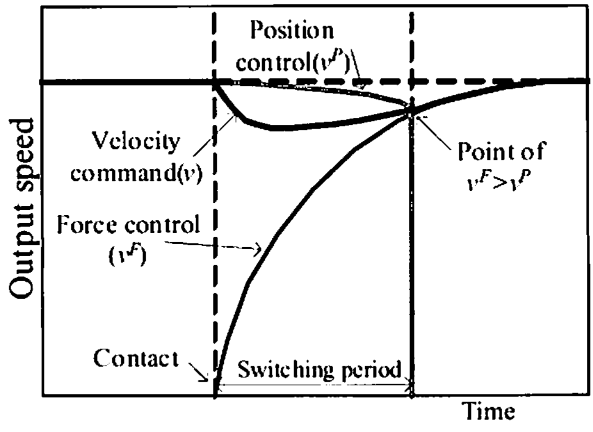

Figure 8. The concept of the motion switching process.

control mode when the condition $v^F \geqslant v^P$ is met:

$$v = \alpha v^F + (1 - \alpha)v^P, \tag{8}$$

$$\alpha = v^F/(v^F + v^P), \tag{9}$$

where α is a parameter for interpolation ($0 \leqslant \alpha \leqslant 1$), and v^F and v^P are velocity commands of the force and position controllers.

5. EXPERIMENTS

5.1. Control parameters

The purpose of the experiments is to examine the effectiveness of the system in accordance with the aforementioned specifications of the virtual wall. The gains of servo-compensators were experimentally set at the range of non-overshoot of the panel position. The parameters used for the experiment were as shown in Table 1.

5.2. Switching process

Figure 9 illustrates the experimental results of the motion switching process. Figure 9a shows the contact force and velocity command of the simple switching method, and Fig. 9b shows the experimental results by the switching process method. Here, *v(output)* is a velocity command to the manipulator, and *v(PT)* and *v(FT)* are the velocity commands from the position and force-tracking controller, respectively. The results in Fig. 9a show that switching from position to force control by a simple switching causes a discontinuity of wall panel motion with a sudden speed change. Figure 9b shows the experimental result using the motion switching process and can be seen that the motion discontinuity problem has been improved. At the moment of contact of the user's hand, the fluctuation of the wall

Table 1.
Parameters for the experiment

Items	Data
Maximum tracking speed	151 mm/s
Operating range X-, Y-, Z-axis	450, 450, 300 mm
θ	23°
Limited pushing force	40 N
K_P^P	3.75
T_D, T_I, T_{Dm}	0.67, 1.0, 1.0 s

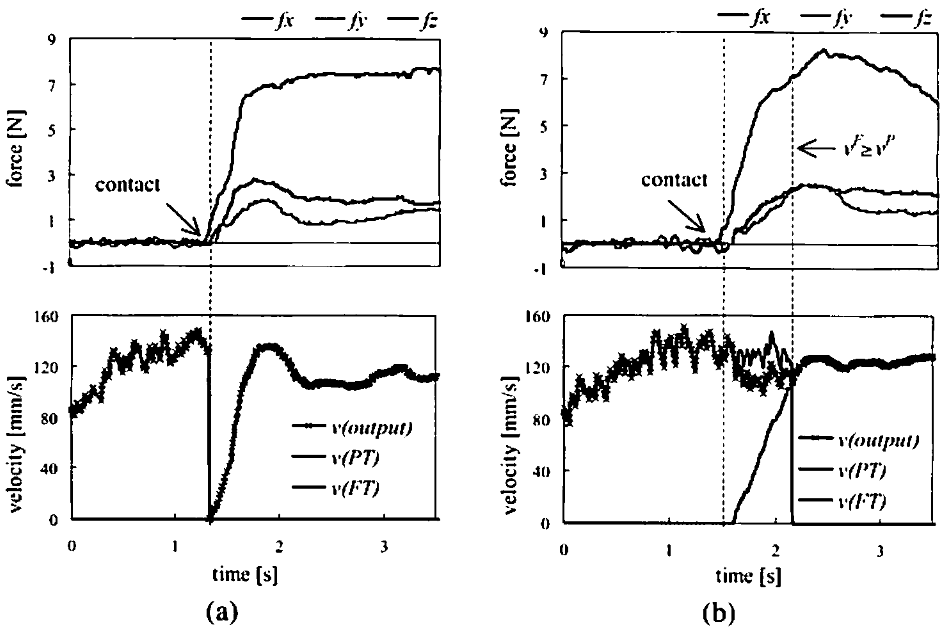

Figure 9. Velocity command of both switching methods. (a) Simple switching. Top: contact force; bottom: velocity command. (b) Switching process for hybrid tracking. Top: contact force; bottom: velocity command.

panel speed has been suppressed below 15% of the moving speed and the change of panel motion was smooth.

5.3. Evaluation of contact tracking

The setting of this experiment is that the user must move their hand in a square trajectory at a constant speed. During the movement, the hand moves to contact and trace the wall panel.

The experimental results in Fig. 10a show the contact force and position of a hand and a wall panel with the position tracking, and those in Fig. 10b show the experimental results with the hybrid tracking. (X_p, Y_p) represents a wall panel position and (X_h, Y_h) represents a hand position. The results are summarized as below.

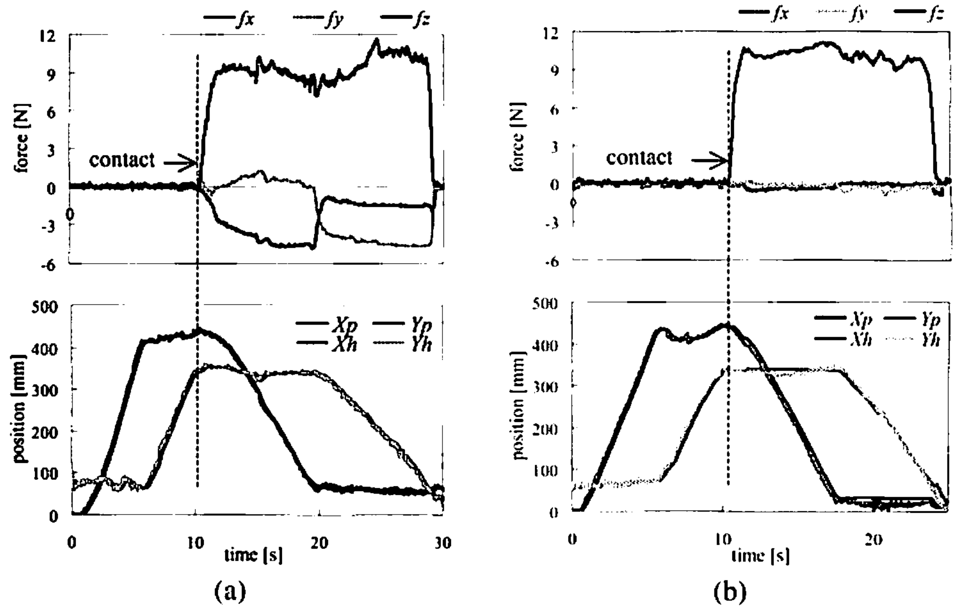

Figure 10. The experimental results of position and hybrid tracking. (a) Position tracking. Top: contact force; bottom: X–Y position. (b) Hybrid tracking. Top: contact force; bottom: X–Y position.

(i) In the complete contact situation (after the dashed line), the hand was hardly tracked by the wall panel due to the high stiffness of the manipulator. Therefore, forcibly tracking by the position tracking caused a large-scale contact force to occur as shown in Fig. 10a. In contrast, the experimental result in Fig. 10b shows that the stiffness of the wall panel in the tangential direction is reduced by the use of force-based tracking control and, thus, the occurrence of contact force is comparatively small.

(ii) The position relation of the user's hand and the wall panel illustrates that in the contact tracking mode, force-based tracking control is available to track the position of the hand as by the position tracking in the non-contact tracking mode.

5.4. Evaluation of the friction display function

The evaluation of the friction display function was divided into non-frictional and frictional force-tracking experiments. The setting of the force-tracking experiments was that the user traces the wall panel in a triangle trajectory at a constant speed with a pushing force below 10 N (around 8 N). The control parameters for the force-tracking control were as shown in Table 2.

The results of the force-tracking experiment are demonstrated as summarized:

(i) A non-frictional force-tracking experiment was implemented to determine the maximum tracking force in the non-frictional condition. The result is close to the ideal result when the maximum tracking force is near zero. According

Table 2.
Parameters for the force-tracking experiment

Items	Data
Dead band of tangential force	0.15 N
Contact detective normal force	0.8 N
T_{Dm}, T_{I}, k_{m}	1.0 s, 1.0 s, 0.01 N/mm
$K_{\mathrm{P}}^{\mathrm{F}}$	3.75

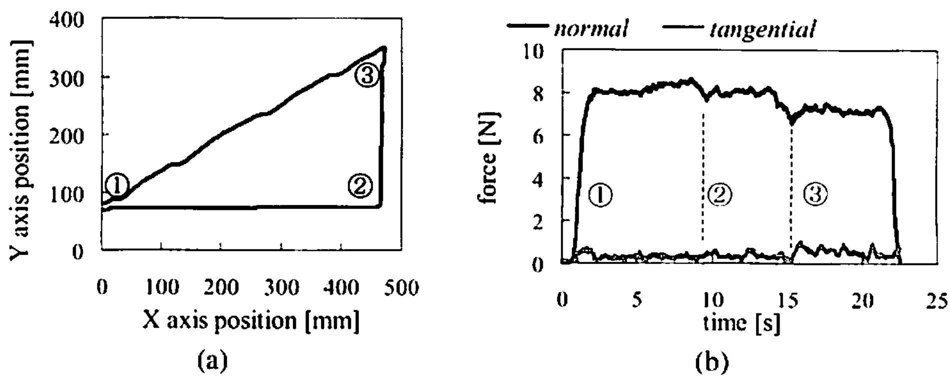

Figure 11. Non-frictional force tracking. (a) X–Y position. (b) The tangential and normal force.

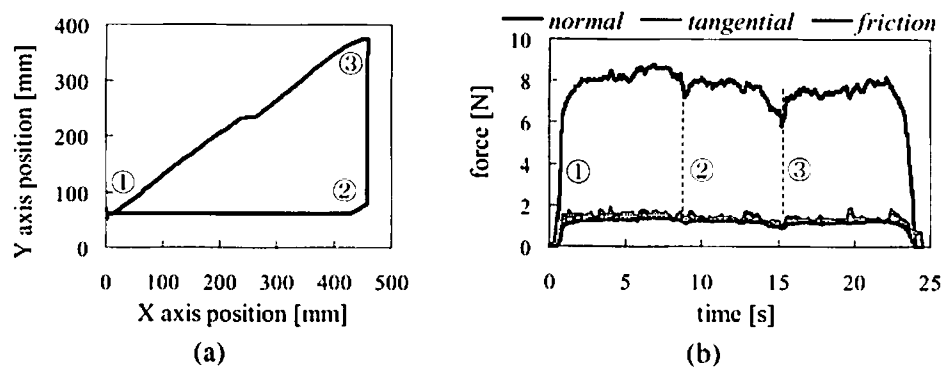

Figure 12. Frictional force tracking. (a) X–Y position. (b) The tangential and frictional force.

to the experimental result in Fig. 11, the maximum deviation of the tangential force and designed force is experimentally obtained at approximately 0.8 N. This result shows us that the wall panel moves lightly along with the hand movement.

(ii) In the frictional force-tracking experiment, the desired value of force control was set to the frictional force, where the frictional coefficient was set at 0.2. The experimental result in Fig. 12 illustrates that the frictional sensation was realized as the tangential force was close to the desired force. The force deviation was experimentally obtained at approximately 0.5 N and the frictional coefficient was realized at 0.21.

(iii) Using the experimental results of several different coefficient values, the realization of frictional coefficient could be derived as shown in Fig. 13. With the setting value at 1.0, the result shows the error of the realized frictional coefficient value was 0.2. This result illustrates that the force control is able to provide the user with the frictional sensation of the virtual wall.

5.5. Stiffness of the virtual wall

The experimental result in Fig. 14 shows the displacement values of the wall panel in the normal direction against the pushing force. According to the average distribution of experimental results, the stiffness of the wall panel in the normal direction was obtained as approximately 21 N/mm. The empirical value of the pushing force of tracing a wall by hand is below 15 N. Therefore, the result can be regarded such that the virtual wall satisfies the feeling of the stiffness of the actual wall.

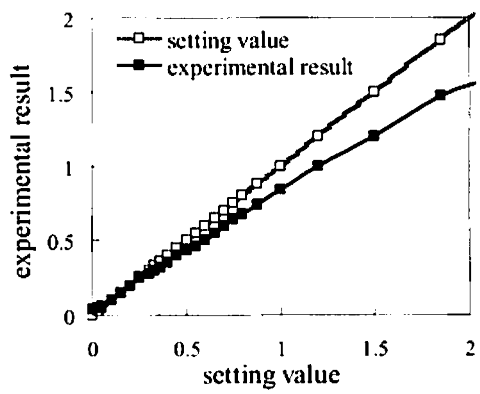

Figure 13. Realization of the frictional coefficient.

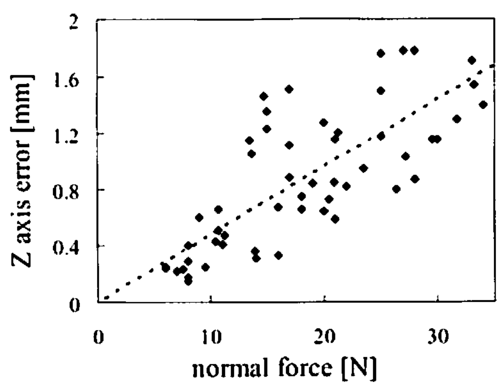

Figure 14. Stiffness of the virtual wall.

6. CONCLUSIONS

In this study, we have constructed a haptic virtual wall system using a small wall panel with force sensors and derived a control method to realize a haptic representation of the virtual plain wall. The main results of this paper are as follows:

(i) A haptic virtual wall system for a walk simulator has been constructed using a three-dimensional hand position sensor system and a small wall panel with force sensors. A movable small plain panel has the role of the main part of the virtual wall and is mounted on a three-dimensional manipulator controlled by PCs to represent a wide plain wall.

(ii) To simulate the natural feel of a virtual wall at the contact and trace by a hand, a hybrid tracking method consisting of position-based tracking and force-based tracking has been developed. Using the method, smooth movement of the wall panel has been realized, avoiding discontinuity of wall panel speed at hand contact.

(iii) Realization of the force control considering the frictional force gives the user a frictional sensation of the virtual wall.

The results of experiments have shown the effectiveness of the proposed control method.

To make the virtual wall more real, more specifications of the virtual wall are needed to get close to the real wall, e.g., tactile rendering of the edge and surface texture of the virtual wall. Furthermore, safety and contact predictive position control for the wall panel is the next crucial problem to be solved. For practical applications, a mechanical servo-tracking system with a high-speed response and a wide three-dimensional range is required.

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REFERENCES

1. F. Kaneko and Y. Ikemoto, Development of evacuee's model by using evacuation simulator, *TVRSJ* 5, 1041–1048 (2000) (in Japanese).
2. Japan National Research Institute of Fire and Disaster, Utilization of virtual reality for fire experience, http://www.fri.go.jp/cgi-bin/hp/index_e.cgi
3. T. H. Massie and J. K. Salisbury, The PHANToM haptic interface: a device for probing virtual objects, in: *Proc. ASME Winter Annu. Meet.*, DSC-55(1), pp. 295–300 (1994).
4. http://www.sensable.com
5. http://www.immersion.com
6. M. Sato, Development of string-based force display: SPIDAR, in: *Proc. Int. Conf. on Virtual Systems and Multi Media*, Gyeongju, pp. 1034–1039 (2002).

7. M. Hirose, K. Hirota, T. Ogi, H. Yano, N. Kakehi, M. Saito and M. Nakashige, HapticGEAR: the development of a wearable force display system for immersive projection displays, in: *Proc. IEEE Int. Conf. on Virtual Reality*, Yokohama, p. 123 (2001).
8. M. Bouzit, G. Burdea, G. Popescu and R. Boian, The Rutgers Master II — new design force-feedback glove, *IEEE/ASME Trans. Mechatron.* **7** (2002).
9. Y. Hurmuzlu, A. Ephanov and D. Stoianovici, Effect of a pneumatically driven haptic interface on the perceptional capabilities of human operators, *Presence* **7**, 290–307 (1998).
10. W. A. McNeely, Robotic graphics: a new approach to force feedback for virtual reality, in: *Proc. IEEE Virtual Reality Annu. Int. Symp.*, Seattle, WA, pp. 336–341 (1993).
11. K. Hirota and H. Hirose, Simulation and presentation of curved surface in virtual reality environment through surface display, in: *Proc. IEEE Virtual Reality Annu. Int. Symp.*, pp. 211–216 (1995).
12. S. Tachi, T. Maeda, R. Hirata and H. Hoshino, A machine which generates a virtual haptic space, in: *IEEE Virtual Reality Annu. Int. Symp. Video Proc.* (1995).
13. T. Yoshikawa and A. Nagura, A touch/force display system for haptic interface, *Presence* **10**, 225–235 (2001).
14. Y. Yokokohji, WYSIWYF display: a visual/haptic interface to virtual environment, *Presence* **8**, 412–434 (1999).
15. D. A. Lawrence, L. Y. Pao, A. M. Dougherty, M. A. Salada and Y. Pavlou, Rate-hardness: a new performance metric for haptic interfaces, *IEEE Trans. Robotics Automat.* **16** (2000).
16. S. E. Salcudean and T. D. Vlaar, On the emulation of stiff walls and static friction with a magnetically levitated input/output device, *ASME Dyn. Syst. Control* **55**, 303–309 (1994).
17. J. E. Colgate, P. E. Grafing, M. C. Stanley and G. Schenkel, Implementation of stiff virtual walls in force-reflecting interfaces, in: *Proc. IEEE Virtual Reality Annu. Int. Symp.*, Seattle, WA, pp. 202–208 (1993).
18. A. M. Okamura, J. T. Dennerlein and R. D. Howe, Vibration feedback models for virtual environment, in: *Proc. IEEE Int. Conf. on Robot and Automation*, Leuven, pp. 674–679 (1998).
19. O. Atoda, Y. Nakamura, M. Tomisawa, K. Yokoyama and T. Imada, A design method of the bipolar allocation and coordinates calculation algorism in a magnetic motion capture device, *J. SICE* **34**, 445–453 (1998) (in Japanese).

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