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Portable Tactile Feedback Interface Using Air Jet

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Abstract

One of the authors have developed portable force feedback displays, to realize the use of force feedback for telerobotic and large-scale virtual environment applications. Tactile sensations as well as force sensations, however, are also required for initial contact detection to virtual objects, because force feedback does not come about prior to any manipulation tasks. In this paper, we have developed a portable tactile display using air jet on a trial purpose to give local shapes of virtual objects and have conducted an evaluation of the perceptual characteristics of the air jet stimulator and the two point difference threshold of index finger pads and thumb finger pads. The tactile display has a eight element array tactile stimulator. In our experiments, subjects are tested to see if they can perceived patterns presented with the device. Two test sets of a cubic geometry shape; the corners, the edge, and the plane surface of the cubic on a PC or a graphics workstation are used to present. It is experimentally verified that the portable display provides the sensation of contact.

Key Words : Virtual Reality, Portable Interface, Tactile Feedback, Air Jet Stimulation

1. Introduction

In order for users to operate manipulation tasks in a large-scale virtual environment, such as the CAVE[1], with feeling presence and with maximum freedom motion, it is necessary for users to feedback haptic sensations from the virtual environment by *portable* force and/or tactile feedback interfaces[2]. Because the user receive haptic feedback from the simulation. On the other hand, nonportable haptic feedback interfaces that are mechanically grounded to a desk, ceiling, or floor, have the advantage of their ability to off-load the actuator weight from the user. The disadvantage of nonportable is a reduction in the user's freedom motion.

There is a growing need for users to interact virtual object in a large-scale virtual environment and a telemanipulation. The portable force feedback interface using pneumatic pipe (or bellows actuators) have been developed by Tanaka et al. (1996)[3][4]. Tactile sensations as well as force sensations, however, are also required for initial contact detection to virtual objects because force feedback does not come about prior to any manipulation tasks. For this reason, we have designed an interface providing tactile stimulations. Tactile stimulation can be achieved various ways, being used for virtual environment systems include mechanical pins activated by piezoelectric crystals, shape memory alloy, solenoid, vibrations from voice coils, temperature from thermoelectric heat pump ,or pressure from pneumatic systems[5]-[7]. We use pneumatic stimulation, compressed air jet to press against the finger pads. The portable interfaces to actuate the user's receptor and motion have to be simple design, light, compact, and safely wearable devices, because the portable interfaces can be used with mechanically grounded on the user's body. Considered providing perceptions of the local shapes in virtual objects to finger pads with maximum freedom motion, the strength of the interface exploiting air-jet actuators consists in its capability of light, simple, and compact structure[8]. In this paper, a prototype model of the tactile-feedback interface using pressurized air-jet have been developed. This interface can be mounted on a finger tip and provides the sensation of initial contacts and local geometry shaped patterns such as corners, edges, and flat surfaces around a cubic object.

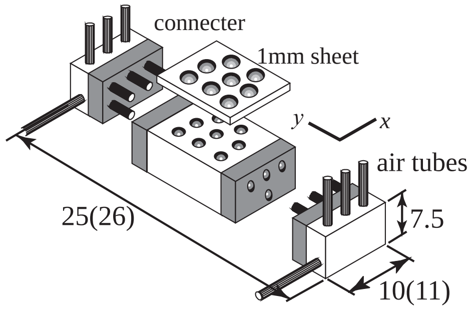
In the next section the developed tactile display is formerly presented. It is important factor to determine the dimensions of the array of the air jet nozzles for the tactile display. To the authors' knowledge, it is the first work to consider a two-point-difference threshold for air jet stimulus. Section 3 presents an experimental evaluation for users' perception stimulated by the air jets. The two-point-difference threshold for an index finger and a thumb are identified to determine the array of the nozzles. The experimental results are applied to the developed tactile display system. In section 4, a system performance of pneumatics for the air jet are clarified. Section 5 and 6 present case studies of perceptual characteristics in virtual environments using the tactile display. A two dimensional virtual cube and three dimensional virtual environment are used as tests of touch sensation. The paper concludes the tactile display can provide the similar sensations of a typical cubic object.

2. Tactile Display

Figure 1 shows (a) the tactile display construction and (b) its appearance. The developed tactile display represents the local object shapes by pressurized air jet from a nozzle array that has a eight element array tactile stimulator. An air jet nozzle that has a diameter of 0.6 mm, with elements spaced 2.6 mm apart in x-direction and 2.8 mm in y-direction for index finger, and 3.1 mm in x-direction and 3.4 mm in y-direction for thumb. These array dimensions are determined by experiments described in Section 3. The display device has a dimension of 25 x 10 x 7.5 [mm] for index finger and 26 x 11 x 7.5 [mm] for thumb. It has a total weight of 22 g. The device uses a pneumatic system to separate the display device from the driving mechanism, enabling a small and light weight display. The phase of the air jet from each nozzle is controlled by a binary-state valve supplied with 0.4 MPa compressed air pressure. The air jet from a nozzle outlet mouse sends up to finger pads. The output force and characteristics of the air jet system are discussed in Section 4.

3. Experimental Evaluation of Two-Point-Difference Threshold for Air Jet Stimulus

User's perception[11] stimulated by the jets is also affected by the nozzle placement, i.e. the distance between centers



(a) Construction of tactile display

(b) Appearance

Fig. 1 Tactile display using air jet

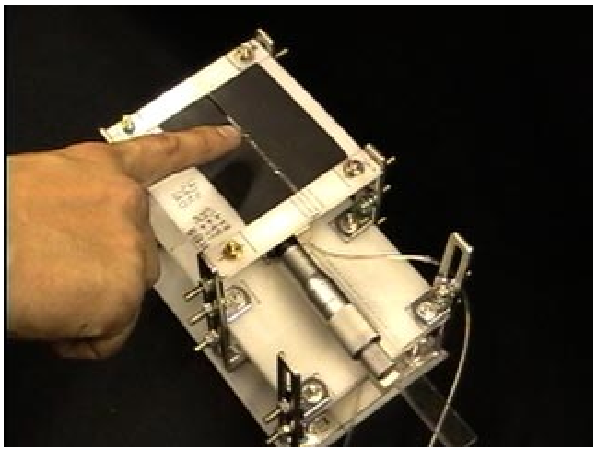


Fig. 2 Apparatus to determine two-point-difference thresholds

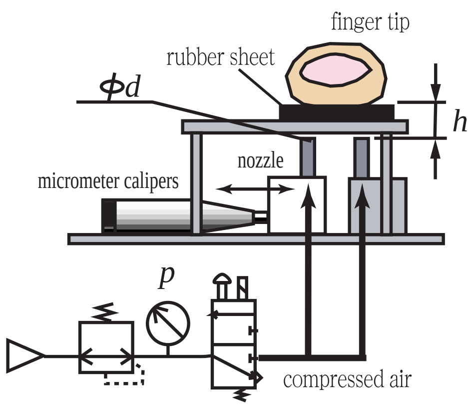


Fig. 3 Setup of the apparatus

of the nozzles not to exceed the two-point-difference threshold of finger pads. We conducted an evaluation of the threshold of an index finger pad and a thumb finger pad in an experiment, in order to design the nozzle placement.

Figure 2 shows an apparatus to determine the two-point-difference threshold. The apparatus is consisted of a pair of air jet stimuli. The nozzle separation distance (center to center) is adjusted by the micrometer calipers attached to one side of nozzle shown in Figure 3.

For the psychophysical experiment to measure the threshold, three factors are used and varied in increments of two steps. The three factors are tabulated in Table 1. The supplied air pressure *p* varying from 200 to 400 kPa in increments of 100 kPa, the air gap between a nozzle outlet and a finger pads *h* varying from 1.0 to 3.0 mm in increments of 1.0 mm, and the nozzle diameter *d* varying

Table 1 Factors for psychophysical experiments.

supplied air pressure *p* [MPa]	0.2	0.3	0.4
nozzle diameter *d* [mm]	0.6	0.8	1.0
gap distance *h* [mm]	1.0	2.0	3.0

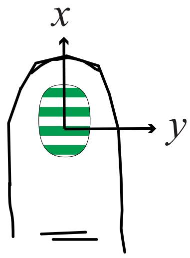
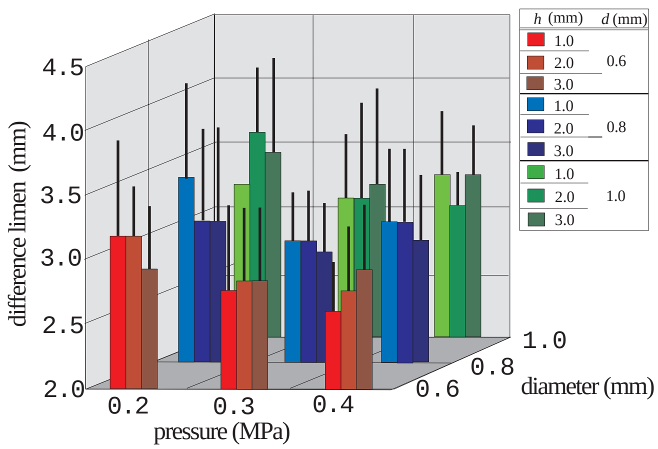
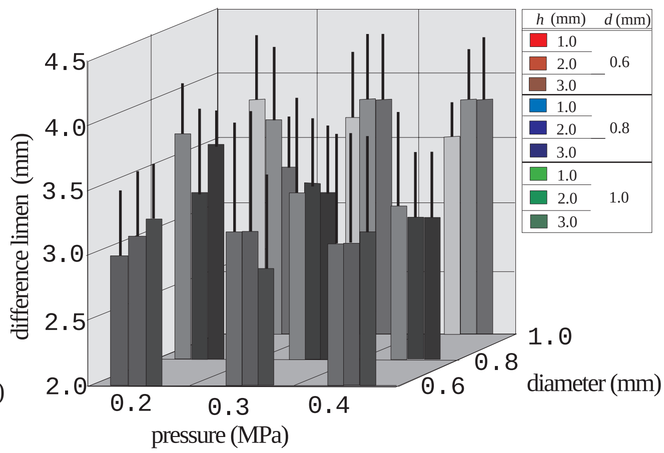


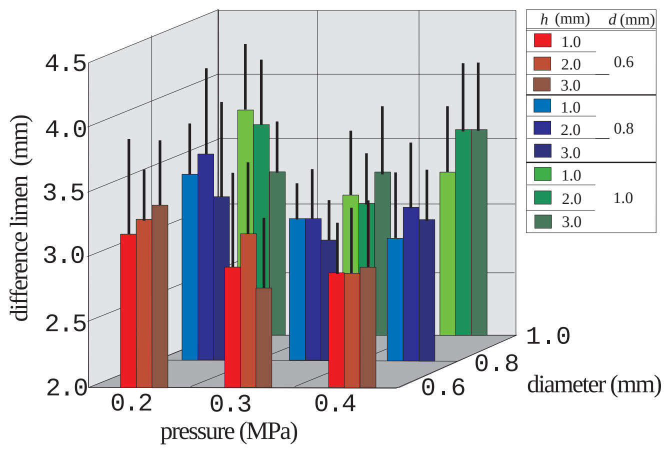
Fig. 4 Definition of axes for a finger pad.



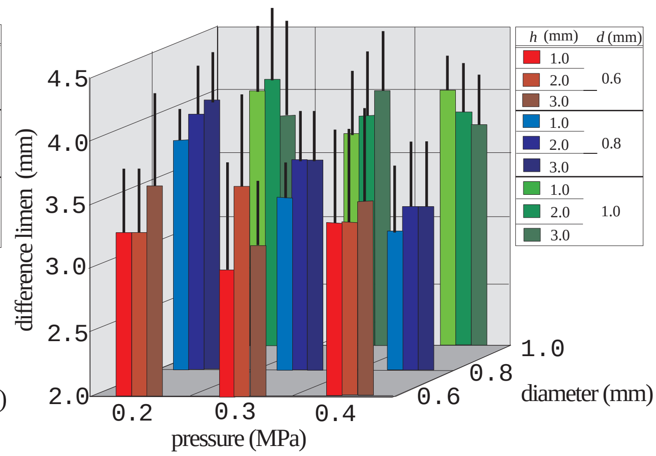
(a) *x*-directional threshold of index finger pad



(c) *x*-directional threshold of thumb finger pad



(b) *y*-directional threshold of index finger pad



(d) *y*-directional threshold of thumb finger pad

Fig.5 Two-point-difference threshold of index and thumb finger pad from 0.6 to 1.0 mm in increments of 0.2 mm are varied to measure the threshold. We investigate the threshold of the scratched area in the x-direction and in the y-direction, shown in Figure 4. Consequently, 27 sets of two-point-air-jet stimulus are used in each direction of a finger pad. A total of ten subjects, all right-handed men, raging from 21 to 24 years, is participated.

Subjects rest their finger tip on the slit as shown in Figure2, wearing a blindfold and headphones to mask any auditory and visual cues, and given verbal instructions before provided a few initial practice stimuli. To assess the thresholds, a method of limits with ascending and descending blocks of trials is used in conjunction with an adaptive, single staircase procedure. One side of stimulus translate along an axis in steps of 0.1 mm.

Figure 5 shows the two-point-difference threshold: (a) in the x-direction of index finger, (b) in the y-direction of index finger pad, (c) in the x-direction of thumb finger pad, and (d) in the y-direction of thumb finger pad.

A set of three histogram bars side by side indicates the mean threshold at h = 1.0 mm (left bar), 2.0 mm (middle), and 3.0 mm (right). All x-directional thresholds on an index finger have lower value than that of y-directional, and significantly lower than that of thumb's. Regardless the gap h, the thresholds on an index finger take minimum values at the set pressure p = 0.3 MPa with the set pressure increment, and decrease with the set nozzle diameter decreasing.

The values that have relatively small at p = 0.4 MPa, d = 0.6 mm, and h = 1.0 ; 2.6 mm, 2.8 mm, 3.1 mm, and 3.4 mm, are used from the result to design the developed tactile display as small as possible.

4. Pneumatic System Performance

Air jet stimulation has the advantage of simplicity, light weight, and lower cost than vibrotactile of electrotactile approaches. Furthermore, air jets are noninvasive and do not produce pain. For the above advantages, however, pneumatic actuators including air jet, may have lower system bandwidth than for electrical actuators because of air compressibility. Therefore it is important that the time to compress air in the nozzle into appropriate pressure to stimulate user's finger pads. In case of air jet actuators the volume of air to compress get small, the system bandwidth is significantly affected by the operational characteristics of control valves. So we investigated the operational characteristic of a control valve.

Figure 6 shows the frequency characteristic of the binary-state single solenoid valve (KOGANEI 010E1) we used for the tactile display under the supplied pressure to the valve (i.e. the primary pressure) 0.4 MPa. The output force from a nozzle varies with the secondary pressure, which means air pressure at an outlet port of a control valve. The output force from a nozzle is estimated with a following model.

Figure 7 shows an apparatus have a tube line from up stream of a control valve to an air jet nozzle and its model. We theoretically obtained the air pressure out of the nozzle

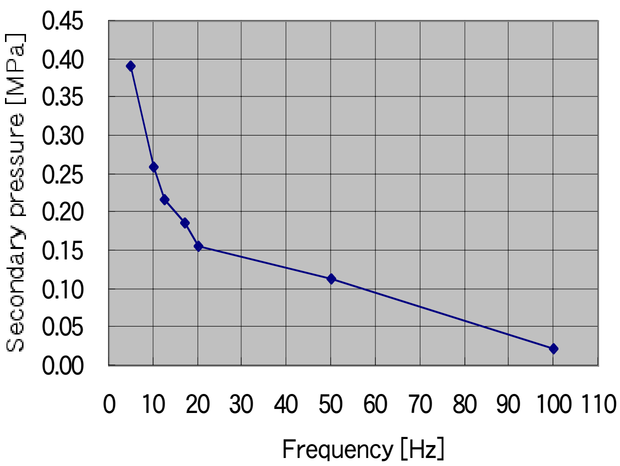


Fig. 6 Operational frequency vs. Secondary pressure of a control valve

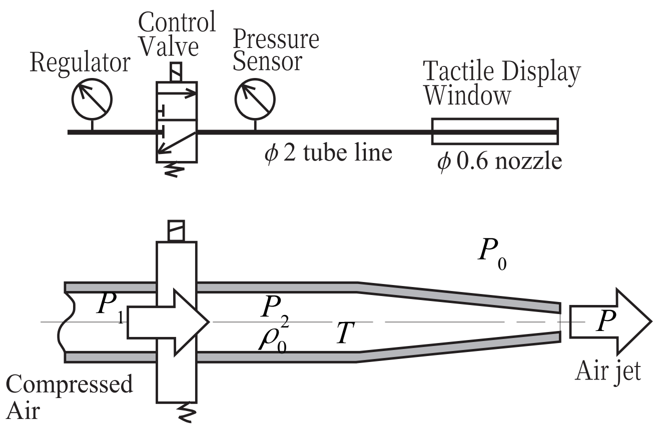


Fig. 7 one dimensional adiabatic compressible fluid in a convergent nozzle model

outlet with hydromechanics of compressible fluids[9]. From the primary pressure P_1 at a control valve and the secondary pressure P_2 at the valve i.e. in the nozzle, output pressure of the nozzle can be calculated under assuming that there is no pressure-loss through the elbows and pressure sensor, no construction at the joints, and no tube friction. Furthermore, this tube line is regarded as a convergent nozzle in which one dimensional adiabatic compressible fluid flows.

Following values were used for calculation.

Compressed air temperature : T [K]
Sonic velocity : a [m/s]
Ratio of specific heat of air : κ
Primary air pressure of the valve : P_1 [MPa](gauge)
Secondary air pressure : P_2 [MPa](gauge)
Absolute secondary air pressure : P_{2abs} [MPa]
Atmospheric pressure : P_0 [MPa]
Density of air : ρ_0 [kg/m^3]

If the critical pressure ratio is less than, $0.5283 < P_0/P_{2abs}$, then the flow in the tube line behave in "the sonic velocity flow" manner. Therefore the air pressure at the nozzle outlet face P [MPa] is equal to the critical pressure P^*. Thus required values under the sonic velocity flow are calculated from these equations shown below.

$$P = P^* = 0.5283 P_2 \qquad (☆)$$

$$\rho = \rho_0 (P/P_2)^{1/\kappa}$$

$$v = a = \sqrt{\kappa P/\rho}$$

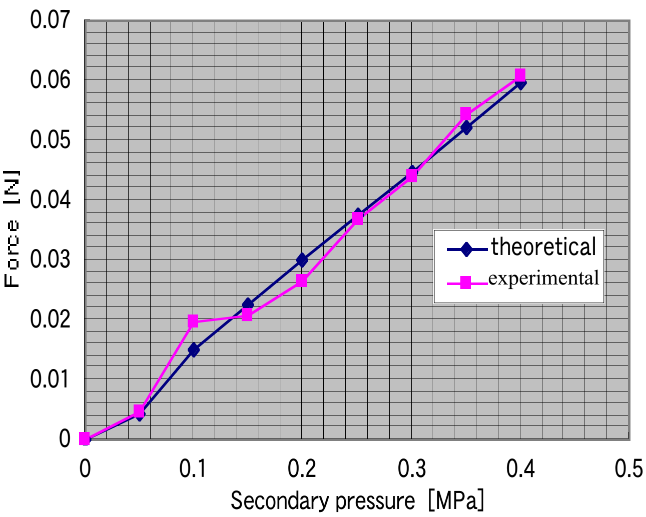


Fig. 8 Displayed force vs. secondary pressure of control at the outlet surface

Figure 8 shows the presented jet force at the nozzle outlet for the valve secondary pressure in the gage. ◆ indicates an theoretical force calculated from nozzle outlet intersection (= $\pi d^2/4$) and pressure obtained by Equation (☆). ■ indicates an actual force measured with an electric balance of scales.

5. Presentation of Geometry Shapes

We conduct an evaluation of user's perceptual characteristics with our tactile display in a simple virtual environment. In an experiment, a cube object is used for presentations of edge, corner, and flat geometry surfaces.

5.1 Experiment

In this experiment, we investigate the perceptual similarity between sensations provided with the tactile display and those provided with touching a real object.

Figure 9 shows the system configuration of the experiment apparatus. The compressed air of 0.4 MPa is supplied to the eight binary-state-valve. Subject wear the tactile display on their index fingertip, hold a mouse as an input of the fingertip position, and move a spherical virtual object around a cubic virtual object surface they are instructed on. The viewed virtual objects are drawn with OpenGL on a Personal Computer (200MHz MPU and 64MB DRAM) simultaneously controlling the eight valves.

We use four static patterns of stimulus presented with the tactile display; (a) x-directional linear set of stimulus (corresponding to an cubic edge), (b) y-directional linear set of stimulus (corresponding to an cubic edge), (c) all

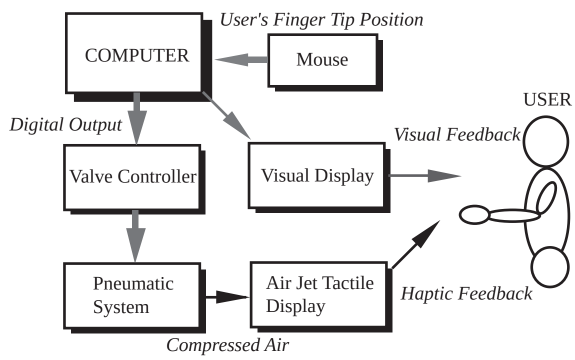


Fig. 9 System configuration for perceptual characteristics

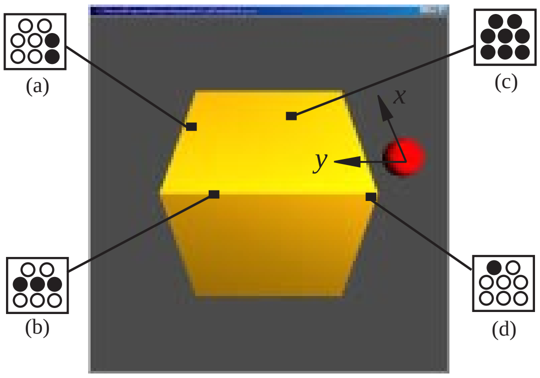


Fig. 10 Virtual cubic object and air jet stimulus (a)-(d) corresponding to collision area.

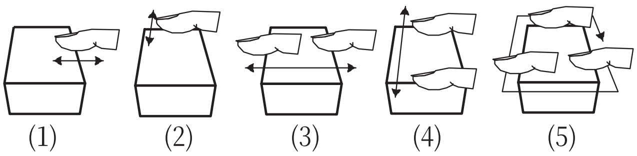


Fig. 11 Five test patterns.

stimulus (corresponding to a flat surface), and (d) one stimuli (corresponding to a corner). These correspondences are shown in Figure10. In combination of these patterns, subjects conduct the five tests of touch on the virtual cubic surface, shown in Figure 11; (1) translation over the edge of a virtual cubic object along x-direction of an index fingerpad, (2) translation over the edge of the object along y-direction of the fingerpad , (3) translation over the object surface from edge to edge along x-direction, (4) translation over the surface along y-direction, (5) translation over the surface around the edge. At the beginning of each test, subjects touch and translate their fingerpad on the real object, just as translate the fingerpad on the virtual object, given verbal instructions before the test.

In comparison with the perceptual similarity between sensations provided with the tactile display and those provided with touching a real object, the answers raging in point from 1-4 are given,

1 point. They have no similarity at all
2 points. They hardly have similarity
3 points. They mostly have similarity
4 points. They have similarity at all.

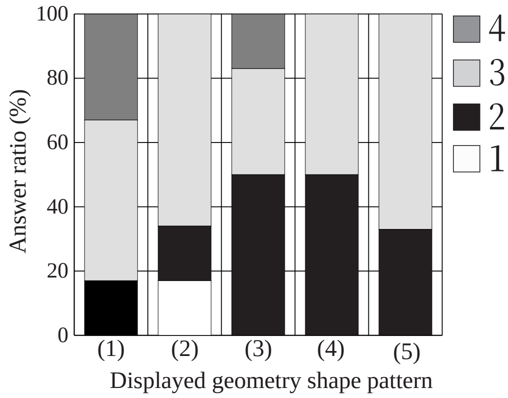


Fig. 12 Results on the perceptual similarity test without visual feedback.

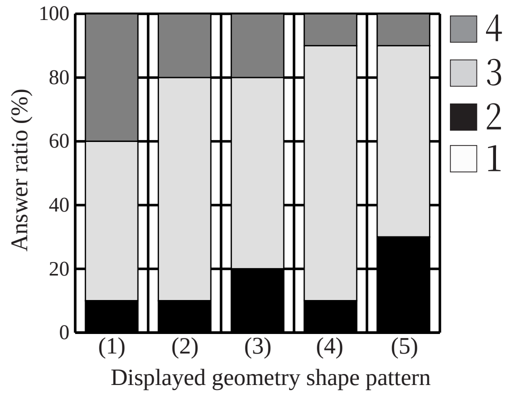


Fig. 13 Results on the perceptual similarity test with visual feedback

A total of ten (six in the case without visual feedback) subjects, all right-handed men, ranging in age from 21 to 23 years, participated. All subjects have an experience in the use of the tactile display.

Subjects choose one answer and say the point from "one" to "four" on each test after provided several trials.

5.2 Experimental Result

Figure 12 shows the results on the perceptual similarity test *without* visual feedback and Figure 13 shows the results *with* visual feedback. These results indicate our tactile display significantly depends on the visual feedbacks from the virtual environment. For the results on Pattern (3) and (4), answer points are lower than other translation patterns, because by touching the flat surface, the pressure between a fingerpad and nozzle outlets totally increases higher with all air jet sending up and causes fingertip perceptions to become dull. But Pattern (1) and (2), i.e. touching on an edge, are relatively marked higher points of answer in Figure 13. Pattern (2) without visual feedback marked lowest points of answer because of the nozzle placement. That the perceptions are influenced by the air jet nozzle arrangement is indicated. Utilized effective visual feedbacks our tactile display can present the similar perceptions well from the results that more than 70 % subjects answered " have similarity" or " mostly have" in the tests.

Fig. 14 Exploration of the cubic object surface in VE

6. Dynamic Perception in Virtual Environment

We present the dynamic patterns of air jet stimulus, changing collision area where a observer touches. A 3-D CG based cubic geometrical surface using the tactile display are experimentally presented without force feedback. Figure 14 shows an operator's fingertip is touching an edge of a virtual cubic object in virtual environment.

The system configuration and setup are shown in Figure 15. The virtual environment are modeled with the WorldToolKit R8 (Sense8) on a graphic workstation (Silicon Graphics Indigo2 Impact10000). The graphic workstation has a graphical refresh rate at 32 Hz. Hand translation and rotation are tracked using the Fastrak (Polhemus) communicating the graphics workstation (WS) at 120 Hz in data transmission rate. The position and movement of the fingers are repeatedly measured using the SuperGlove (Nissho Electronics) at 143 Hz in data transmission rate. Data communications to control the binary state valves uses the BSD socket based communication on the internet protocol.

The operator arbitrarily touches around the surface before asked the tactile perceptions of initial contact to the surface. Some subjects who have experienced the use of haptic interfaces are participated in the task of an exploration of

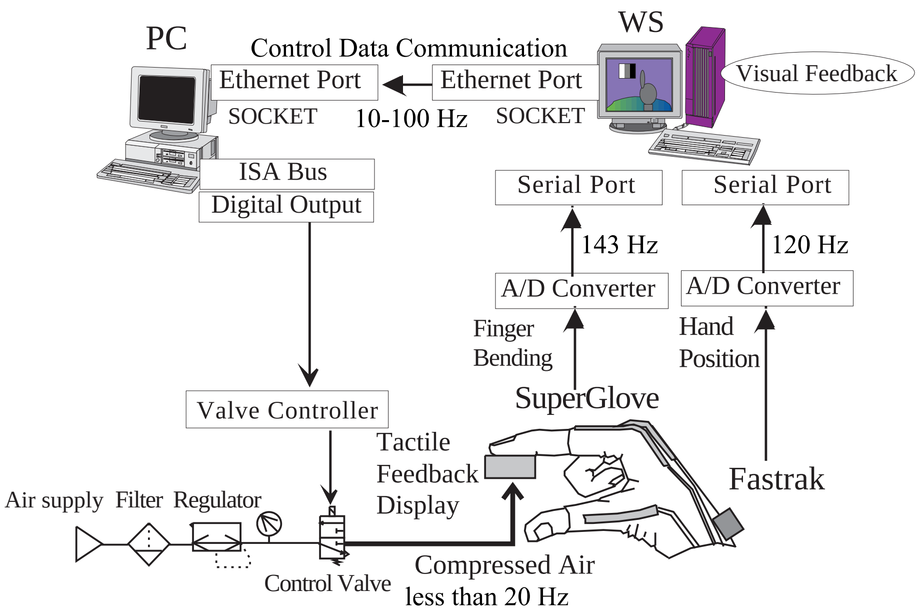


Fig. 15 System configuration for touching in virtual environment.

the cubic surface: touching a corner, an edge, and a flat surface. Depending on particular contact positions of the finger, most subjects suspected, the proper sensation have been hardly displayed but success in providing a flat surface.

7. Conclusions

We have developed the portable tactile feedback interface using stimulators of the pneumatic actuator; air jets, on a trial purpose. The pneumatic actuators is suitable for portable interfaces because of the advantage of simplicity, light weight and cheapness. For the developed tactile display eight air-jet stimulus are used for presentations of local shapes required for initial contact to virtual objects with fingertips. The tactile display are evaluated the performance characteristics through the case studies for subjects. According to the experimental results of case studies, presenting four patterns of geometry shapes, the tactile display can provide the similar sensations of a typical cubic object. The dynamic perception in the three dimensional virtual environment is also evaluated.

The future work with the interface is focusing on the development of providing the tactile perceptions in a large-scale virtual environment. And further evaluation of its psychophysical characteristics and furtheir improvements of the tactile feedback system are inevitable, including reconsideration the nozzle placement to present local shapes of combined objects and enhancement of the display hardware system compactness to be able for users to wear them; the pneumatic system, the controlling hardware, and the motion sensors, and to walk around in a large-scale virtual environment.

Acknowledgments

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