Visio-Acoustic Screen for Contactless Touch Interface with Tactile Sensation

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ABSTRACT

This paper proposes a contactless touch screen that produces tactile sensation just 1-3cm before the actual touch on the screen. The system has a screen, visual projectors, and sensors for finger motion detection, which composes a non-contact touch screen by gesture sensing. In this paper we add a non-contact tactile display using an airborne ultrasound phased array. The key device of the system is a screen that is a scattering plane for visual projectors and transparent for ultrasound. We show the design of the screen and examine the effectiveness through numerical simulations and experiments. The screen has an additional property that stops the air flow going through the screen maintaining the transparency for the ultrasound. We constructed the contactless touch screen system and examined the position sensing accuracy under the tactile support.

KEYWORDS: Contactless touch screen, tactile feedback, Airborne Ultrasound Tactile Display.

INDEX TERMS: H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Haptic I/O; H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Input devices and strategies

1 INTRODUCTION

In this paper, we propose a contactless touch screen with tactile feedback. This system is similar to a usual touch screen but users can feel tactile sensation just 1-3cm before the screen surface. Users can find buttons with tactile stimulation and get tactile feedback for interaction. One of the suitable application scenes of this system in public spaces is shown in Figure 1. The screen displays an interactive guide map in a department store.

Such an interaction system as shown in Fig. 1 but without tactile feedback is one of typical near-future applications of non-contact interactive display using gesture-sensing [1-6]. The visual information is displayed at free location on the screen with the projectors, and the information changes in response to the user's gestures. Since the screen is only a passive scattering plane, there is a rich design freedom in shape and alignment of the display. As the gesture is sensed with remote sensors, physical contacts with the screen are not always necessary for interaction.

Non-contact nature of interface device is preferable for avoiding hygienic problems as well as enabling 3D interaction. Especially in hospitals, non-contact interfaces are desired [4]. But the problem of such non-contact interfaces is they lack tactile feedback. In this paper, we propose adding tactile feedback to these devices. We stimulate the user's finger with the radiation pressure of airborne ultrasound [7] propagating through the screen. Stimulating the finger just before the real touch enables the user to push the virtual buttons more surely and easily without actual contact to the screen. The system requires no prepared devices of the users for feeling the tactile feedback. An example of non-contact interface with ultrasound tactile display is the work by Hoshi [8]. In Hoshi's device, the distance between display and user's hand is as far as 60 cm without the projector screen. In our system, the operation plane is set to about 1cm in front of the display everywhere over it, potentially.

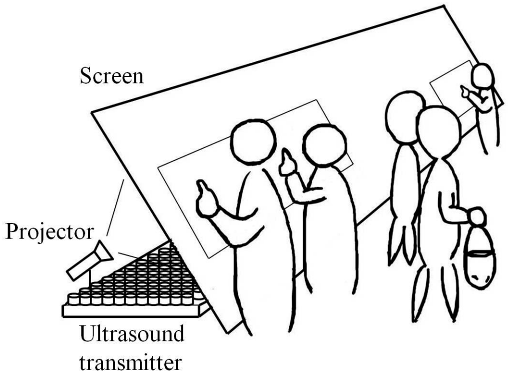

Figure 1. The image of usage in public places.

In order to realize such a system, we need a special screen satisfying the following properties: (1) good scattering plane for displaying the visual projector images, (2) transparent for airborne ultrasound, and (3) cutting off the air flow streaming through the screen. Property (2) is necessary for stimulating the user's skin with the ultrasound coming from the back of the screen. Property (3) is desirable for preventing the fingers from feeling air flow induced by the ultrasound beams. It is known that an air flow is generated along a strong ultrasound stream [9], which degrades the produced tactile feeling in many cases. In this manuscript, we call this screen Visio-Acoustic (VA) screen.

In the following sections, we show the design and prototype of VA screen. We assess its physical property with numerical simulations and experiments, and examine the effect of adding tactile responses to users.

2 DESIGN OF VA SCREEN

The basic structure of our VA screen is shown in Fig. 2. In our first study we use acrylic as the optically transmissive material. We utilize Airborne Ultrasound Tactile Display (AUTD) [7] as the noncontact tactile presentation device. AUTD forms pressure distribution on human skin of sinc type spot by acoustic radiation

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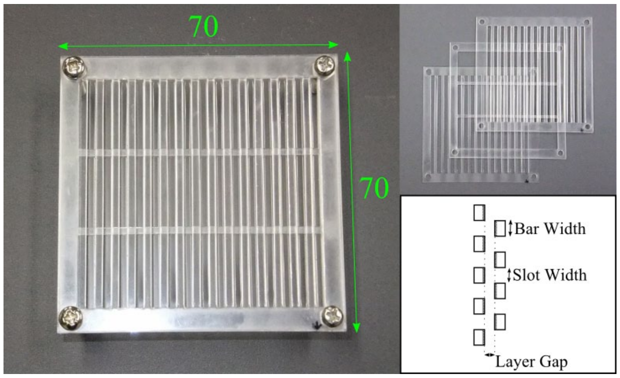

Figure 2. Left: Photograph of VA screen, Right-upper: Photo of each layer, Right-lower: Definition of parameters.

pressure. The spot position is controlled with phased array technique. In order to allow transmission of acoustic wave emitted from the back of the screen, the screen is composed of two slotted layers composed of parallel bars aligned alternately as shown in Figure 2. The two horizontal bars crossing the vertical bars seen in Fig. 2 are inserted to keep the gap constant between the two layers. We calculate transmittance by numerical simulation and explored the best parameters of the VA screen for the highest transmission of acoustic wave. Another important factor is the cut-off property of the air flow generated along the ultrasound beam [9] since the accompanied air flow degrades the tactile feeling. Therefore we select the best parameters to minimize the air flow to pass though the screen keeping the highest transparency for ultrasound.

2.1 Set up of numerical simulations

It is desirable that the thickness of the acrylic plate is as thin as possible to minimize the unevenness of the visual scattering plane. In this experiment, we decided the thickness of acrylic plate to be 1mm for ensuring the mechanical rigidness. The VA screen has two parameters, Slot Width and Layer Gap (Figure 2). Bar Width and Slot Width are always the same to cover screen surface at 50% aperture ratio. First, we conduct numerical simulations for various Slot Width, Layer Gap, and ultrasound amplitudes, and plot the acoustic transmittance and the passed air flow. We use ANSYS for the simulation. In the following subsections, we describe the conditions of simulations and report the results.

2.1.1 Transmission of acoustic wave

Acoustic radiation pressure P[Pa] is proportion to the square of acoustic pressure;

$$P = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where p[Pa] is the RMS sound pressure of ultrasound, ρ [kg/m^3] is the density of air, c[m/s] is sound speed and α is the coefficient depending on reflecting conditions [7]. Therefore, we simulate acoustic waves' propagation first to estimate acoustic radiation pressure.

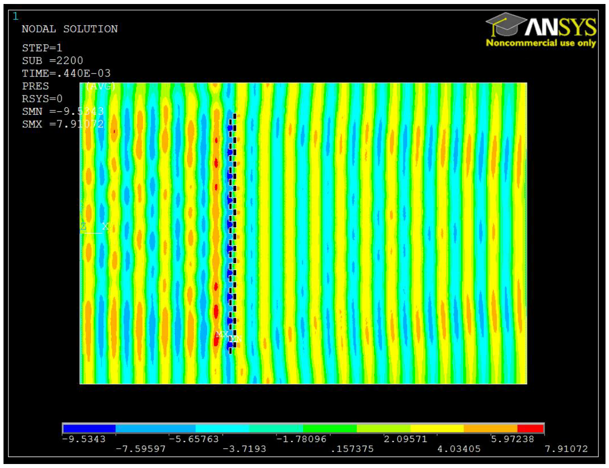

Figure 3. Simulation result of acoustic wave propagation.

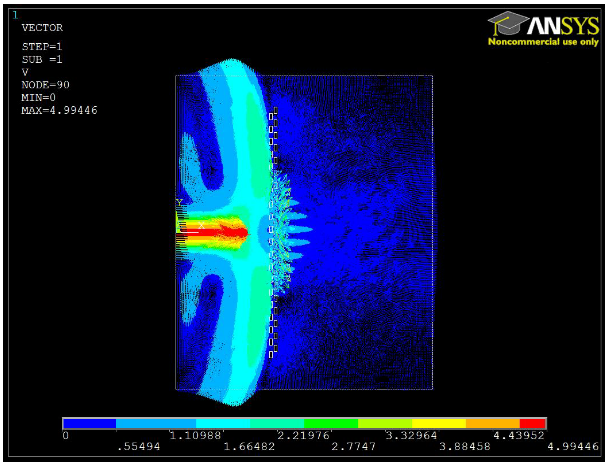

Figure 4. Result of air flow simulation.

One of the graphical results is shown in Figure 3. An acoustic wave is propagating from the left side to the right side. The area for simulation is 100mm x 150mm. The VA screen size is 80mm. The element types are 2D acoustic elements which are called fluid 29. In this simulation, the attenuation during propagating is excluded. The left and right vertical boundaries are assumed to be sound absorbing walls and the top and bottom ones are reflecting walls. In Figure 3, the VA screen is shown as two lines of small black blocks. We assume the surface of each "Bar" of the VA screen to be a perfect reflector since the acoustic impedance is quite different between the air and the solid material. We input a plane sinusoidal wave at 40 kHz from the left boundary. The analysis type is time history response, and we simulate from 0s to 440us. The time 440us is shorter than the time for the reflected wave to reach the evaluated point. Fig. 3 is the pressure distribution at 440us in the condition of 5Pa amplitude input pressure, 2mm Slot Width and 0.5mm Layer Gap. The color bar shows sound pressure of sound [Pa]. In the left side area of the VA screen, the incident and reflected waves are seen. The transmitted wave is seen in the right side area.

We evaluate the transmittance by reading amplitude of a point which locates 1cm apart from the right side of the screen after the amplitude becomes steady. We simulated changing three parameters; input pressure amplitude, Slot Width, and Gap Layers.

2.1.2 Cutting off air flow

One of the graphical results about air flow simulation is shown in Figure 4. Fig. 4 is the velocity distribution in the condition of 5m/s applied velocity, 2mm Slot Width and 0.5mm Layer Gap. The velocities of air flow are expressed by colored vectors. The color bar shows quantity of velocity [m/s].

The simulated area is 100mm x 80mm, which is shorter than acoustic analysis because we don't need to care about reflection. The VA screen size is same as acoustic analysis (80mm). The

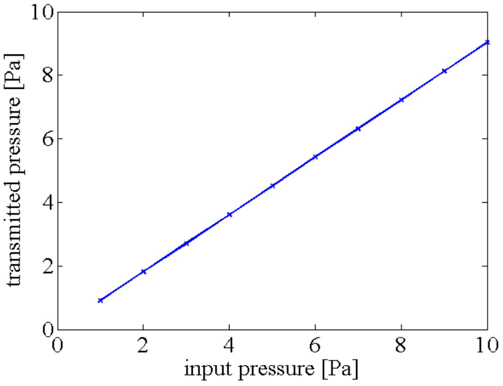

Figure 5. The simulation results of relationships between transmitted acoustic pressure and input pressure.

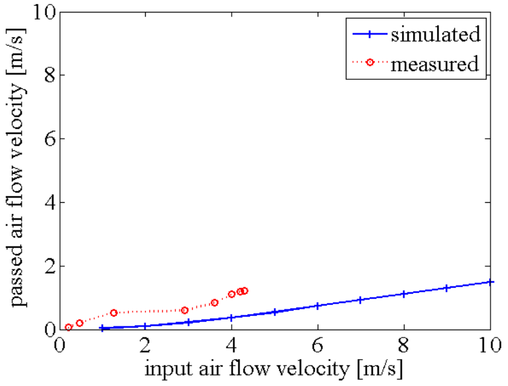

Figure 6. The simulated and measured results of relationships between passed air flow velocity and input air flow velocity.

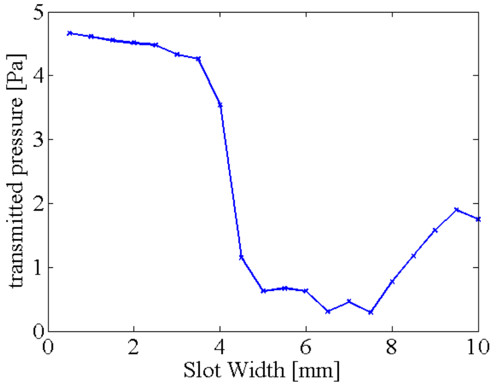

Figure 7. Simulated acoustic transmittance vs. Slot Width.

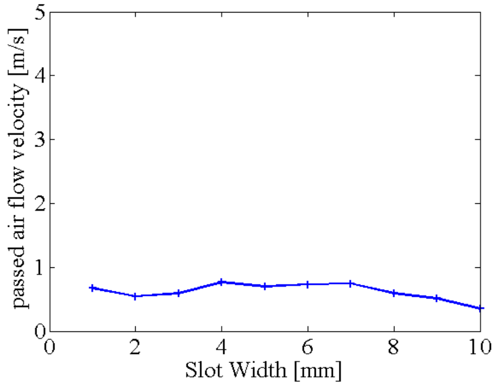

Figure 8. Simulated air flow passing rate vs. Slot Width.

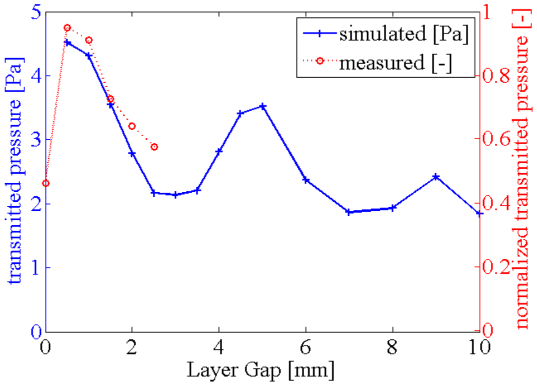

Figure 9. Simulated and measured acoustic transmittance vs. Layer Gap.

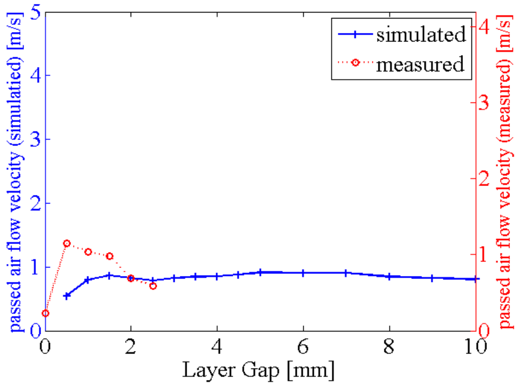

Figure 10. Simulated and measured air flow pass vs. Layer Gap.

analysis type is fluent analysis (element type is fluid 141, which is normally used for modeling fluid systems). We continuously put air flow from the left line and simulated the flow distribution in steady state analysis. We assume air flow velocities are distributed in the Gaussian shape whose half width is 1cm, which is almost equal to the spot size of AUTD. The top, right and bottom lines of the area are set to 0Pa, which is equal to atmospheric pressure. The velocities of nodes attached to the screen surfaces are set to 0m/s for all directions. We evaluate x-direction velocity on the line parallel to the screen and 1cm apart from it to the right-hand. We search the maximum velocity in x-direction and determine it as the "passed air flow".

2.2 Numerical and experimental results of acoustic and air flow transmission

Not only numerical simulations but also experiments were conducted. We made a prototype screen (Figure 2), and measured acoustic wave pressure and air flow for some parameters. We produced a focus by AUTD at 240mm above the transducers array. The AUTD has 14 x 18 -3 = 249 transducers. It makes spot whose diameter is about 1cm and gives 1.6 gram force at the spot. We put an ultrasound sensor where it showed the highest value near the spot, and then, inserted the VA screen 1cm below the sensor. We measured the changes of acoustic pressure and air flow caused by inserting the screen. As the measured values of acoustic

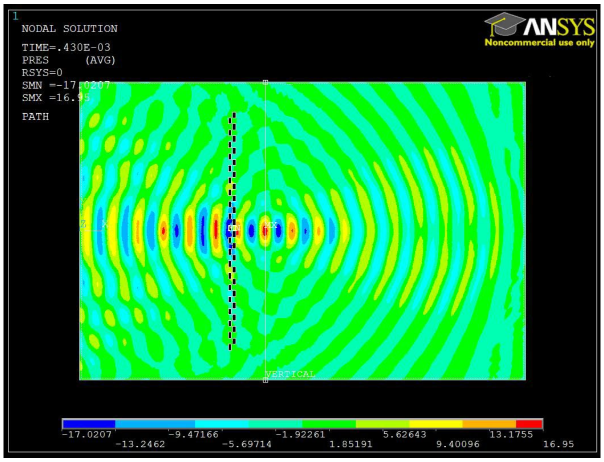

Figure 11. The simulation of making a spot.

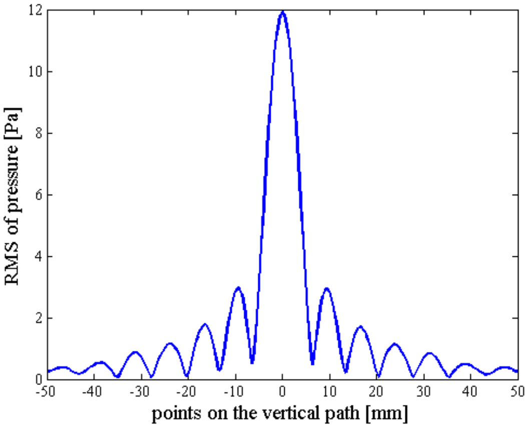

Figure 12. The RMS of pressure on the path crossing the focus.

pressure, we used the peak-to-peak voltage of the sensor output. For measuring air flow, we used hot wire anemometer (VT100S, KIMO). This anemometer can measure air flow from 0.15m/s to 30m/s.

2.2.1 Transmission of acoustic wave

Figure 5 is the relationships between input pressure amplitudes and transmitted ones. In this simulation, Slot Width is fixed to 2mm and Layer Gap is 0.5mm. The graph shows they change linearly. Figure 7 shows the changes of transmitting rates when Slot Width is changed. The input pressure is fixed to 5Pa and the Layer Gap is 0.5mm. From this graph, we can say the rates keep high when Slot Width is smaller than the half of wave length. Figure 9 is the dependency on Layer Gap. The left side vertical axis is the measure for the simulated values and the right one is for the normalized experimental values. In both results, Slot Width is fixed to 2mm. We plotted the simulated sound pressure at the evaluation point with the marks of “+” and the solid line. The incident sound intensity from the left side is 5Pa for all the Layer gaps. We also plotted the experimental data with “o” and the broken line. The data are normalized ones by the incident sound pressure, that is, the plotted value is the ratio of the measured sound pressure at the evaluation point for each screen condition to the pressure measured without the VA screen. The simulated data shows transmitting rates change cyclically and the peak level decreases as Layer Gap become longer. The measured data shows similar tendency to simulated results. Both data show the best Layer Gap in our simulations and experiments is 0.5 mm.

2.2.2 Cutting off air flow

Figure 6 shows the relationships between applied velocity and passed air flow. We plot simulated results (solid line marked “+”) and measured results (broken line marked “o”). In this graph, Slot Width is fixed to 2mm and Layer Gap is 0.5mm. Both results show the same increasing tendency of the passed flows as applied flow velocities are increased. However, these graphs don’t show as clear linearity as acoustic wave showed. Figure 8 shows the changes of passed flow when Slot Width is changed. The applied velocity is 5m/s and Layer Gap is 0.5mm. This graph shows the passed flow rates are relatively insensitive to changes in our simulation and experimental setting. Figure 10 is about changes of Layer Gap in the condition of 2mm Slot Width. The solid line marked “+” is the results of simulation and broken one marked “o” is measurement. The maximums of y-axis are the results when we don’t put the screen. At short distance, measured results show different tendency to simulated results. However, it is common that changes of Layer Gap don’t influence the efficiency of cutting off air flow.

2.2.3 The best parameters

Taken together the results above, Slot Width and Layer Gap influence only acoustic transmitting rate and the properties of the air flow cutting off are not sensitive to the parameters. Therefore, we decided parameters in terms of wave transmitting rate. For the use as visual display, it is desirable that Slot Width and Layer Gap are as small as possible. This requirement doesn’t conflict with the simulated results. However, we have limitations in terms of the fabrication and its durability of the screen. Thus we decided the best parameters are 2mm Slot Width and 0.5mm Layer Gap. In these conditions, the screen pass only 27 % of air flow in velocity and transmits 95% of sound wave amplitude, which corresponds to 90% in acoustic radiation pressure.

2.3 Confirmation of focusing

Lastly, we confirmed the changes of propagating phase caused by the screen. Figure 11 is the result of simulation at the time when the focused point shows maximum values. We input phase adjusted wave pressure $p(t,r)$ to nodes on the left line in order to make focus at 1cm away behind the screen. $p(t,r)$ is represented as

$$p(t,r) = A\sin(2\pi f(t+\frac{|r-r_f|}{V})) \qquad (2)$$

where r is pressure applied node’s coordinates, r_f is the focal point, A is amplitude [Pa], f is frequency [Hz], t is time [s] and V is the velocity of sound [m/s]. In this simulation, r = (0, y coordinates of nodes), r_f = (52.5, 0), A=5, f=40000, V=340.31 are applied. Figure 12 is the RMS of pressure about the nodes on the vertical path which crosses the focus. Figure 11 and 12 show phase’s changes by the screen are negligible and a focus is formed at the desired point.

3 CONTACTLESS TOUCH SCREEN

3.1 System set up

We set up a contactless touch screen system with the VA screen discussed previously (Figure 14). The distance to center of the screen from AUTD is 230mm and the spot is made 1cm above the screen. AUTD is the same as the one used in the previous measurement and we use a projector commercially available

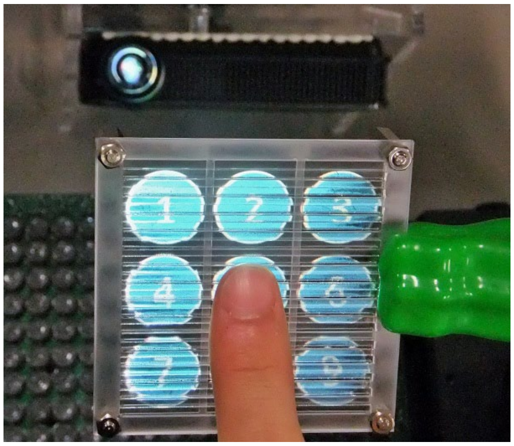

Figure 13. Photo of position recognition experiment.

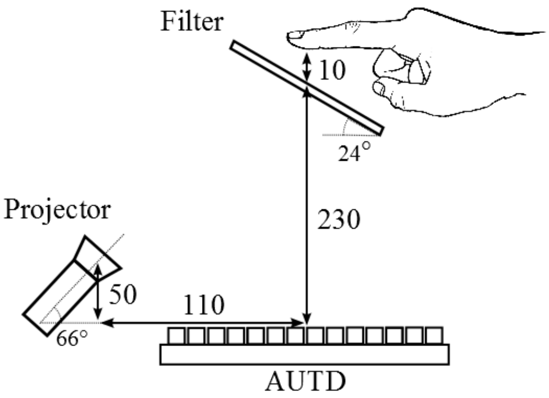

Figure 14. Set up of position recognition experiment.

(Optoma PK320). By the existence of tactile sensation, we can haptically find the places where button images are positioned. To confirm this, we conduct a position recognition test for six subjects.

3.2 Experiments

To confirm the effect of tactile support we conducted a position recognition test. Subjects looked at projected images of 9 buttons arrayed 3x3 at intervals of 20mm as shown in Figure 13. We made a tactile spot by AUTD at one of the buttons with 30Hz vibration and asked subjects where the spots existed. Subjects searched the place by forefinger of their dominant arm and answered the number indicated by the tactile stimulus. We did not give any instruction on the height from the display surface where the subjects should put their fingers. The diameters of buttons were 16mm. All 6 subjects were male and their dominant arms were right. We showed 5 times of each 9 numbers in random order, and subjects answered 45 times in total. Subjects listen to white noise while experiment for removing other cues and protecting them from ultrasound.

3.3 Results

The percentages of correct answers are shown in Table 1. Most of the subjects could detect the positions with high probability except for subjects C. 95.8% of his mistakes were answering the number in the row directly above the correct number. For example, he chose number 4 when the spot were made at number 7. In this situation, he could feel the stimulation produced at number 7 with his finger cushion. We guess he confused the stimulation given to his fingertip with finger cushion.

Table 1. The results of position recognition test.

subjects	A	B	C	D	E	F
validity[%]	100	95.6	44.4	100	100	100

4 CONCLUSION

In this paper, we proposed a contactless touch screen with tactile sensation. Adding tactile feedback enhances the usability of the non-contact touch screen system which is preferable for avoiding hygienic problems in public space applications as well as enabling 3D interaction. To achieve this system, we proposed a Visio-Acoustic (VA) screen which is a scattering screen and transparent for acoustic wave for tactile feedback. In addition, the screen is able to cut off the air flow passing through the screen. The screen we proposed is two layers of bar arrays aligned alternately. In order to decide parameters of the screen, we conducted simulations and examined the screen in terms of the acoustic wave transmittance and cutting off property of air flow. The results of acoustic wave propagation showed Slot Width and Layer Gap should be as short as possible in our experimental settings. On the other hand, air flow doesn't show obvious differences by these parameters. Based on these results, we selected 2mm Slot Width and 0.5mm Layer Gap, which are our current limit of fabrication and durability. In these parameters, the screen can transmit 95% of the wave amplitude and pass only 27% of the air flow in the velocity. The contactless touch screen system with this VA screen can notify the places where images are projected by tactile sensation. The user test showed 5 subjects of 6 identified the correct position by tactile support with high probability. The future work is to attach finger tracking mechanism and achieve interaction of finger movement and image projection.

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