# VacuumTouch: Attractive Force Feedback Interface for Haptic Interactive Surface using Air Suction

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## ABSTRACT
We present VacuumTouch, a novel haptic interface architecture for touch screens that provides attractive force feedback to the user's finger. VacuumTouch consists of an air pump and solenoid air valves that connect to the surface of the touch screen and suck the air above the surface where the user's finger makes contact. VacuumTouch does not require the user to hold or attach additional devices to provide the attractive force, which allows for easy interaction with the surface. This paper introduces the implementation of the VacuumTouch architecture and some applications for enhancement of the graphical user interface, namely a suction button, a suction slider, and a suction dial. The quantitative evaluation was conducted with the suction dial and showed that the attractive force provided by VacuumTouch improved the performance of the dial menu interface and its potential effects. At the end of this paper, we discuss the current prototype's advantages and limitations, as well as possible improvements and potential capabilities.

### Author Keywords
Air suction; attractive force; interactive surface; haptic interface; VacuumTouch.

### ACM Classification Keywords
H.5.2. [Information Interfaces and Presentation]: User Interfaces—*Haptic I/O*, *User-centered design*.

## INTRODUCTION
Research and design in the field of haptic interfaces for touch screens have been developing rapidly. User performance has been improved, e.g., selecting and clicking visual widgets on the screen [9, 27], because the touch screens themselves do not have mechanical-button-like haptic feedback. Additionally, the haptic interface also enriches the realism of the visual environment. For example, a user is able to perceive the texture or material of an image [3, 12]. Many techniques and systems that offer a variety of realistic haptic sensations have been explored.

The haptic sensation induced by the interface can be divided into two categories, namely tactile or force. Tactile sensation is usually induced by mechanical skin deformation that fires the cutaneous receptors. Vibratory sensation that is included in one of the tactile sensations is often used for haptic interactions on a touch screen. Force sensation is most often induced by the tension on the muscle, tendons and joints. Using force sensation as feedback for a touch screen can guide the user's hand to the desired position and assure manipulation.

Furthermore, force sensation falls into three categories in terms of direction of actuation from the surface to the finger, namely lateral, repulsive, or attractive. Systems that offer lateral direction force feedback have previously been established [28, 34]. Saga and Deguchi, for example, developed a lateral-force-based haptic interface for touch screens, employing motors and wire strings that pull the user's finger from the corners of the screen [28]. A repulsive sensation is induced by a force whose direction is from the surface toward the finger. It is often used for simulating mechanical button clicking on the surface [9, 27]. An attractive force is induced by a force whose direction is from the finger to the surface. For instance, Weiss et al. developed FingerFlux, which attracts the user's finger to the surface with a permanent magnet attached to her finger and electromagnetic actuation [35]. While we have

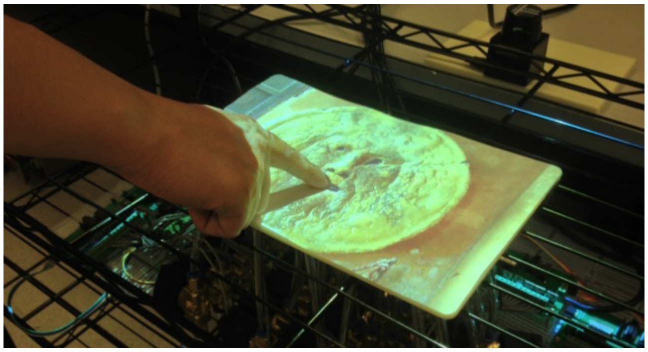

**Figure 1. VacuumTouch: user can feel the attractive force to the surface without requiring holding or attaching an additional device. Here, user is feeling the attractive force from La Bocca della Verità.**


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categorized haptic sensation into four groups, i.e., tactile, lateral force, repulsive force or attractive force, a combination of some sensations is possible because the sensation is continuous.

Most previous haptic interfaces actuate either devices held by or attached to the user (e.g., stylus, nail) or the surface of the touch screens. The latter allows the user to easily interact with the surface because she does not have to hold or attach an extra device. However, to the best of our knowledge, there is no attractive-force-providing technique that does not require holding or attaching a device.

In this paper, we present a novel haptic interface architecture for touch screens, VacuumTouch, which provides attractive force sensation. VacuumTouch consists of an air pump and solenoid air valves that connect to the surface of the touch screen and suck the air above the surface where the user's finger makes contact. The contributions of this work are: 1) the implementation of an interactive surface that can attract a user's finger without requiring her to hold or attach an additional device; 2) demonstrations of graphical user interface (GUI) applications with VacuumTouch; 3) an evaluation of user performance. The paper first reviews previous literature concerning haptic interaction techniques on a touch screen. Next, we describe VacuumTouch's system architecture. Then, we demonstrate its applications, including an evaluation of the user study. Finally, we conclude the paper with a discussion of our method's pros and cons and our future research direction.

## RELATED WORK

### Attractive Force Feedback

This section reviews previous literature on haptic interfaces for touch screens involving attractive force feedback.

Although they did not develop it for touch screens, Akamatsu and Sato established the multimodal mouse [1], which was one of the earliest haptic interfaces to apply attractive force sensation to general computer input devices. The mouse included an electromagnet and a solenoid-driven pin, and they provided attractive force from the mouse to the iron mouse pad and tactile sensation, respectively. They demonstrated that their mouse shortened the response time for the targeted selection task.

Weiss et al. developed FingerFlux [35], which consists of electromagnets beneath the surface and a permanent magnet attached to the user's finger. While this technique is quite similar to Akamatsu and Sato's multimodal mouse, they implemented repulsive force as well as attractive force. Furthermore, FingerFlux can not only provide haptic sensation on but also above the surface. They demonstrated that FingerFlux could significantly reduce drifting time when the user operates on-screen buttons even without looking. While this technique has shown the potential of attractive force, it requires attaching a magnet to the user's finger.

Bau et al. developed Teslatouch, which employs electrovibration to control electrostatic friction between the surface and the user's hand [3]. Electrostatic friction generates an attractive force on the surface, which results in friction sensation. Although it is possible to provide attractive force without requiring the user to hold an additional device, the sensation is only felt while a finger is moving on the surface.

In addition to magnetic and electrostatic forces, controlling air pressure can generate attractive force (e.g., air suction). A great deal of research has explored techniques for providing haptic feedback using air pressure control. The following section reviews literature on these techniques.

### Haptic Feedback with Air Pressure Control

Applying air pressure control to haptic interfaces has generally been explored to achieve contactless haptic feedback. As far as we know, the first attempt was Heilig's Sensorama [14], which is famous as one of the earliest immersive virtual reality systems and provides tactile sensation using a fan. Since fans are cost- and power-efficient, many virtual reality systems employ it [5, 6, 7, 19, 22, 29]. Most of these systems provide tactile and repulsive force sensation for the user.

Another method for providing haptic feedback using air pressure control employs speakers. Hoshi et al. developed a tactile feedback device using an array of ultrasonic speakers [15]. By precisely controlling the phase of waveform output from ultrasonic speakers, the device can provide tactile feedback in the air (above the surface) without holding or attaching a device. While it is also possible to provide repulsive force sensation, it is difficult to provide attractive force sensation using this method.

Hashimoto and his colleagues developed a haptic interface that employs audio speakers [13, 18]. The user holds the speaker by hand while the speaker vibrates the air between the speaker cone and her palm [13]. When the frequency is very low (e.g., 1 Hz), she feels both a repulsive force and an attractive force. However, it is difficult to provide continuous attractive force using this method due to its mechanical limitations.

The employment of air compressors and air valves also has been explored. Most previous work presents haptic interfaces that provide tactile or repulsive force sensation via jets of air [2, 10, 16, 31]. For example, Suzuki and Kobayashi established a three dimensional visual and haptic interactive system with 100 air-jet nozzles, where the user interacts with a stereoscopic image with a stick [31]. The nozzles connect to an air compressor through electric valves that control the output air, and blow the air to the stick, which results in repulsive force sensation.

Besides jets of air, an air vortex is another haptic feedback technique [11, 30], which provides tactile or repulsive force sensation. Compared to jets of air, its stimulus is more

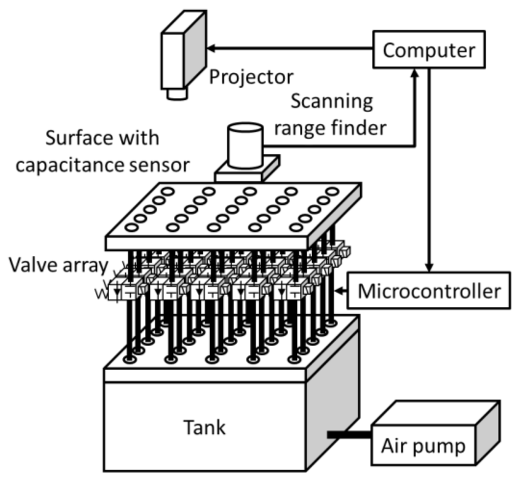


**Figure 2. The prototype system architecture.**

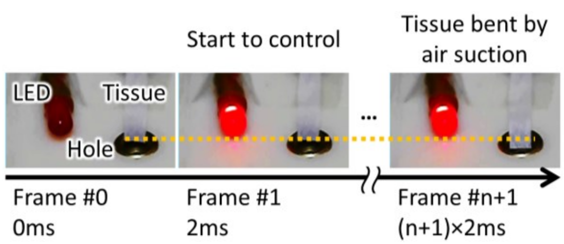


**Figure 3. The setup to investigate the latency between the microcontroller's order and the generation of the suction force. Typical duration is 10ms (#n=5 with a 500 fps).**

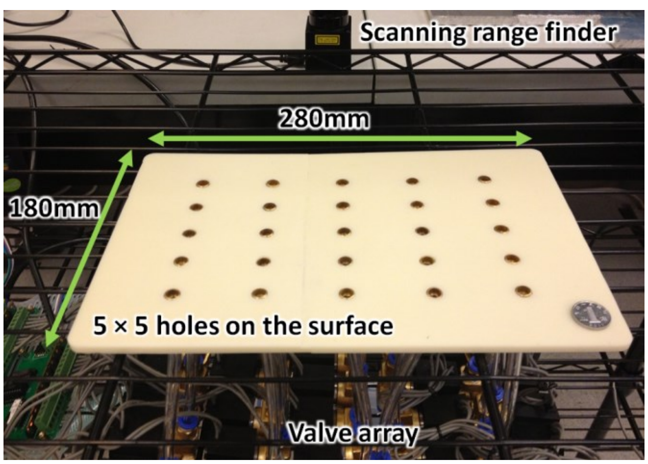


**Figure 4. A VacuumTouch prototype surface with a workspace of 280 × 180mm and 5 × 5 holes.**

convergent and travels longer distances. However, it is also difficult to provide an attractive force using this method.

Haptic feedback systems that employ air suction have already been established as well [20, 26]. However, the idea is not to provide attractive force sensation, but to induce tactile pressure sensation based on a haptic illusion that causes humans to be unable to discriminate suction from compression when the skin is pulled by negative air pressure through a small aperture [20]. Matoba et al. developed a haptic interactive surface, ClaytricSurface, which employs an air pump and electromagnetic valves to control air suction [21]. Yoshimoto et al.'s Haptic Canvas [33] and Follmer et al.'s Jamming User Interfaces [8] also employ a suction system, though they suck not only the air, but also liquid. However, they use suction to control the density of the particle/fluid with which the display is filled and control the softness and shape of the display.

## PROTOTYPE SYSTEM

To build an interactive surface that provides attractive force feedback without requiring a user to hold or attach an additional device, we have combined a projector-based visual display and a touch sensor (an infrared (IR) scanning range finder and a capacitance touch sensor). Our VacuumTouch prototype consists of an air vacuum pump, an air tank and an array of electric magnetic air valves connected to holes on the surface as shown in Figure 2.

### VacuumTouch Surface

*Architecture*

We employed a rotary vane dry vacuum pump (Sato Vac Inc., ODF-50W) because it produces less pulsation than other types of vacuum pumps. For example, diaphragm pump seems to have an unexpected effect (e.g., vibration) on haptic sensation. The pump connects to the tank (5.5 liters) with an air tube, which temporally retains air pressure. The tank connects to the holes of the surface through the electric magnet air valves (Amico, VX2120-X64, DC12V (10.2W), normally closed) with air tubes one by one. The diameter of the holes is 1/8" (9.728mm), small enough to be covered with the tip of the finger.

Switching the valve array was controlled by a microcontroller (NXP Semiconductors, mbed NCP LPC 1768) through parallel-out shift resisters (Toshiba, 74HC 595) in a Serial Peripheral Interface (SPI) bus and field effect transistors (FETs). Our current prototype only has simple on/off control.

*Feedback specification*

According to an air pressure gauge installed on the tank, the maximum suctioning capability is about 0.085MPa. This means that while the holes with open valves are completely covered with a finger(s), the force applied to the fingertip is about 6.3N (640gf). When one valve opens and its hole is not covered, the air pressure drops to 0.030MPa. In addition, the air pressure drops 0.015 and 0.008MPa as two and three valves open, respectively. When more than two valves are open, it is hard to feel a force sensation. In informal testing, we found that 0.015MPa was enough to fix the finger onto the hole. However, it may vary with other physical conditions, such as dragging on the surface and hovering over the hole. In addition, subjective sensation also depends on the type of interaction.

The loudest module is the air pump, which produces 63dB(A) at the user's position. While the air valve also produces a sound when it opens and closes, it seems to

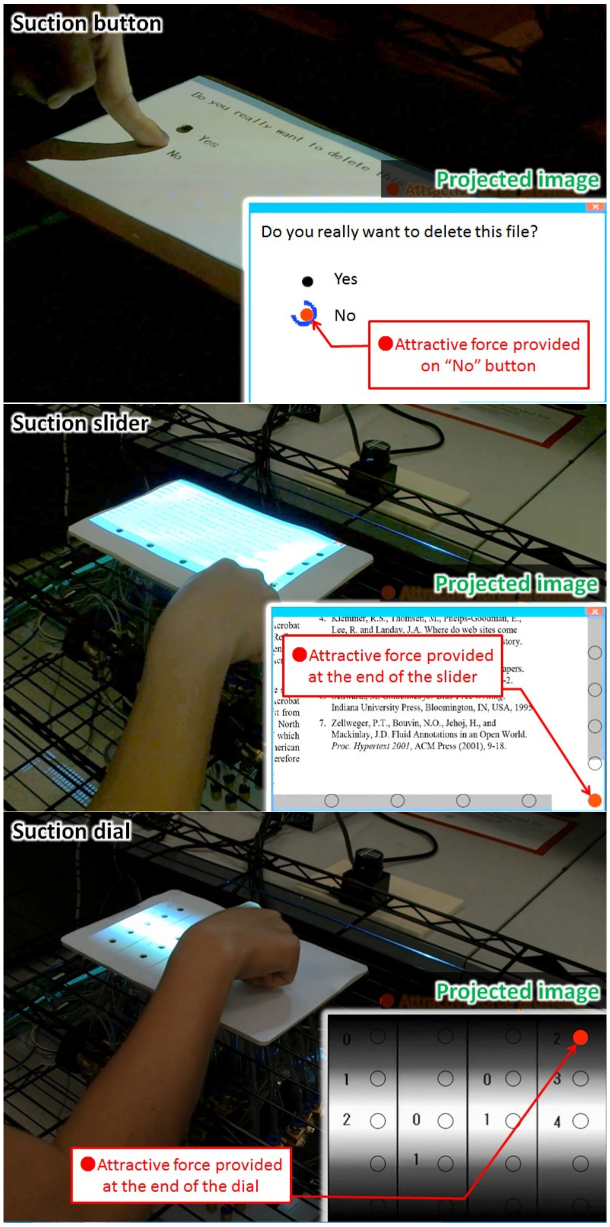


**Figure 5. Three GUI applications of VacuumTouch: Top) suction button; Middle) suction slider; Bottom) suction dial. Red circles indicate the attractive force provided.**

enhance the subjective force sensation, probably due to cross-modal effect.

#### *Latency*

While the microcontroller is able to activate and deactivate all the FETs in less than 1ms, the generation of the attractive force takes significantly more than 1ms due to the activation time of the electric magnet and the travel time of the air from the tank to the hole on the surface.

We investigated the current system's latency between the microcontroller and the generation of the suction force with the setup shown in Figure 3. We put one sheet of thin tissue on the hole and put a light emitted diode (LED) next to the hole. First, the microcontroller simultaneously lit the LED and ordered an air valve to open it while the air pump was driving, as shown in the middle of Figure 3. Then, the edge of the tissue was moved into the hole as shown on the right side of Figure 3. This was monitored by a high-speed camera with a 500 fps. We observed that the LED started lighting and the tissue completely bent from the video and counted the number of frames between them (n in Figure 3). We repeated this observation 10 times. The number of the frames ranged from 4 to 6 and the average was 5. Thus, the latency was around 10ms. With the same setup, we measured the time for turning off the suction force and found it was around 40ms. A possible improvement for the latency is discussed in the section on limitations and improvements.

### System Configuration

As illustrated in Figure 2, we set the scanning range finder (Hokuyo Automatic Co., Ltd., URG-04LX-UG01) and capacitance sensor (single electrode) to measure the two dimensional position of a finger on the surface and detect finger contact with the surface, respectively. The projector (BenQ Co., MS616ST) is installed above the surface. First, the touch sensor measures the user's touch input and sends it to the computer. Then, the computer processes the input and outputs the visual image and control signal for the valve array to the projector and the microcontroller, respectively. The refresh rate of the whole system is currently 10 Hz, which is based on the touch sensor. The prototype has a workspace of 280 × 180mm and 5 × 5 holes on an acrylonitrile butadiene styrene (ABS) resin plate as shown in Figure 4. The touch sensor can be compatible with another input technology of similar capability, such as a camera vision and IR grid touch sensor.

Our prototype system provides a haptic interaction without requiring a user to hold or attach an additional device. This allows her to easily experience the interaction as shown in Figure 1, where she feels an attractive force from *La Bocca della Verità*.

## APPLICATIONS

In this section, we describe three possible GUI applications of VacuumTouch, namely a suction button, a suction slider, and a suction dial. While we think that an effective application would be in an entertainment system, such as *La Bocca della Verità* in Figure 1, or video games, the evaluation of an entertainment system is in general difficult. To assess the usability of our system as an interface, this paper focuses on GUI.

### Suction Button

The top of Figure 5 shows an example of the suction button, in which the system is asking the user if she really wants to delete an important file (e.g. a system file), i.e., asking “Yes” or “No.” The user needs to press and hold the button for two seconds to determine the input. In other words, she is able to cancel her selection within two seconds by releasing her finger from the surface.

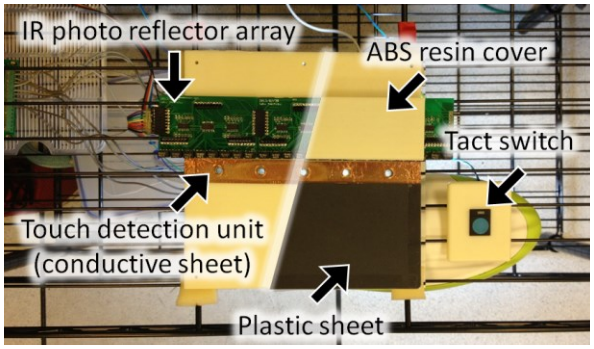


**Figure 6. The experimental setup: the touch sensor (the IR photo reflector array and the induction-based touch detection unit) installed on the surface and the tact switch located on the right side of the surface. The IR sensor covered with the ABS resin and the thin, black plastic sheet fixed along the touch detection unit.**

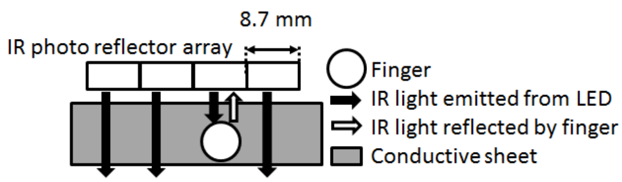


**Figure 7. Principle of an IR photo reflector array to detect one-dimensional finger position.**

Because the system knows how important the file is, it recommends not deleting it. Thus, the system provides the attractive force at the hole on the "No" button. In addition to recommending options, the system would be able to warn the user with a repulsive force by blowing air if the current setup had an air injection function.

### Suction Slider

The middle of Figure 5 shows an example of the suction slider, where the user is browsing a document. She is reading the document while scrolling with the slider bars on the right and bottom. Her attention is on the content of the document, rather than the slider bars. Thus, it is possible that she will still try to scroll through a document even when it comes to the edge, which makes her uncomfortable. The suction slider addresses this issue by forcibly stopping her finger on the slider. This results in intuitive haptic cues as if the slider physically contacted the end.

### Suction Dial

The dial menu interface is used in a number of touch screen applications, such as alarms. One of the issues for the interface is that it is hard to know where the end of the dial is. As seen in existing methods, a visual spring effect is provided at the end of the dial, where the dial still can be scrolled toward the same direction after the end has been reached and returns to the end when the finger is released. However, it is impossible for this to happen with a physical dial.

In order to simulate a realistic dial menu interface, we created the suction dial, as shown at the bottom of Figure 5. VacuumTouch provides a suction force at the end of the dial, where a user physically cannot scroll the dial in the same direction, which is difficult for existing haptic interfaces.

## EXPERIMENT

We conducted an experiment to investigate the effect of the attractive force sensation provided by VacuumTouch. We picked up the suction dial menu for the experiment. The task of the experiment was to find the end of the dial where the attractive force was provided. The task allowed us to quantitatively evaluate the usability of the attractive force as an interface and compare it with the existing technique.

### Participants

24 people (20 males and 4 females; ages between 20 and 28; all right-handed) participated in the experiment.

### Material

To study the effect of the attractive force on the dial task, we redesigned some parts of the system.

#### *Touch sensor*

The suction dial menu was built on visual and haptic dragging interaction. For visual interaction, Ng et al. developed a high-speed touch screen that produces only 1ms of latency [23]. They demonstrated a user can detect about 10ms of latency and prefer lower latency interactions. For haptic interaction, the tolerance of latency depends on the types of input and feedback (e.g., a 5ms latency has an impact on perceived stiffness for the pressing interaction [24]; a 40ms latency impacts on perceived texture for exploring surface interaction [25]). It is generally agreed that a system should be controlled with a 1-kHz refresh rate. However, the current system has only 10-Hz refresh rate due to the touch sensor. Furthermore, the 10-Hz refresh rate was temporally too low to see any difference in the task times between feedback conditions (see the Procedures and Results section).

Achieving a 1-kHz refresh rate with visual interaction is difficult because a well-designed configuration of the touch sensor and projector is needed. In addition, the purpose of the experiment was to investigate the effect of the attractive force feedback on the dial task. Thus, we decided to use a normal projector whose refresh rate was 60 Hz.

To achieve the 1-kHz haptic interaction, we replaced the scanning range finder and the capacitance sensor with an IR photo reflector array and an induction-based touch detection unit, as shown in Figure 6. The principle of the IR photo reflector (Lite-On Technology Co., LTH-1550-01, interval is 8.7mm) array was to emit IR light and detect its reflection as illustrated in Figure 7. It can detect an object that is located a few centimeters in front of the IR photo reflector. The induction-based touch sensor usually uses power-line noise (50 or 60 Hz) for detection. However, this experiment required faster sampling, i.e., 1 kHz. Thus, we put an inverter (around 20 kHz) based fluorescent light under the surface for a high-speed induction noise generator.

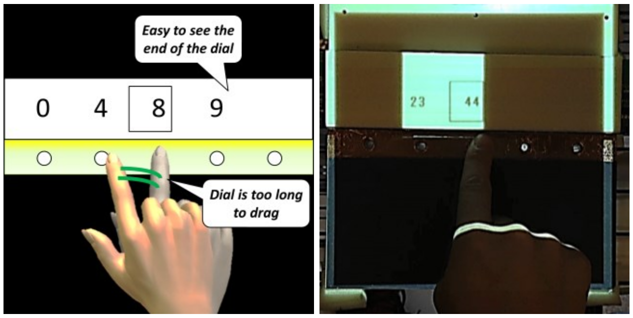


**Figure 8. The pilot study's setup with five numbers of the dial projected (left) and the experimental setup with two numbers of the dial projected (right).**

Combining these two sensors enabled the microcontroller to detect the participant's dragging gesture and control the attractive force feedback with a 1-kHz refresh rate. While the sensor measures the position in only one dimension, it is passable for this dial task experiment, where a user needs only a one-dimensional scroll.

*Touch screen surface*

We made five holes in a row at the center of the 200 × 200 × 50mm ABS surface. The diameter of the holes and the intervals were 1/8" (9.728mm) and 36mm, respectively. We fixed the touch sensor as shown in Figure 7. To project the image, the sensor was covered with the ABS resin. Thus, in this setup, while the participant's finger did not directly touch and manipulate the image of the dial menu, it allowed the participant to clearly see the numbers without occlusion. In addition, to support the participant dragging her finger in a straight line, the thin black plastic sheet was fixed along the conductive sheet.

A vibration motor was also installed on the back of the surface for providing vibration as described in the following section. We measured the vibration using an accelerometer (Yamaichi Electronics Co., Ltd., Yamco 110B and 4101) on the touch screen surface. The peak amplitude and frequency were around 0.5G ($4.9m/s^2$) and 130 Hz, respectively. The amplitude plateaued 100ms after activation. A tact switch was installed on the right side of the surface. It was used for completing the selection task.

**Design**

In the pilot study, we projected five numbers of the dial above each hole and a box in the center position, as illustrated on the left side of Figure 8. We asked participants to set the end of the dial to the box where the attractive force was provided. We faced some difficulty in conducting the user study with the five numbers. First, the participants tended to scroll the dial not by dragging, but by flicking, because they tried to scroll the dial with minimum motion. In this case, it was difficult to provide the attractive force because their finger did not reach and contact the hole. Even if we instructed participants not to flick, they felt fatigue toward the end of the task and tended to use the flick operation. Second, the participants relied on visual images rather than the attractive force. The end of the dial could be seen before it came to the box. Thus, users easily found the end of the dial without any haptic cues.

Based on the pilot study, we decided to project two numbers of the dial and the box as shown on the right side of Figure 8. In this setup, participants dragged their finger to the hole and could feel the attractive force at the end of the dial. In addition, the end of the dial could not be seen until it came to the box. This setup allowed us to investigate the effect of the attractive force while participants were dragging their finger.

We presented four conditions to investigate the effects of the attractive force. The first condition was attractive force (AF), where the attractive force was provided from when the end of the dial came to the box to when the finger was released. The second condition was no feedback (NF), where the image of the dial became frozen when the end of the dial came to the box. The third condition was visual spring (VS), where the image of the dial could be moved by dragging even when the end of the dial passed through the box. This allowed participants to see a blank space after to the end. When participants released their finger, the end of the dial returned to the box. The forth condition was vibration (VB), where vibration was provided by the vibration motor at the same time as AF.

We presented five dials that had 4, 6, 8, 10 and 12 numbers, respectively. At the beginning of the dial, the number was always 0 and the number increased when participants scrolled the dial to the left. At the end of the dial, the number was randomly determined from 11 to 99. The other numbers were also randomly determined without overlap. The interval distance between the numbers was always 36mm (i.e., the same as between the holes).

Thus, the experiment had 20 (= 4 feedbacks × 5 dial lengths) conditions. The collected data included the task time and error numbers. We recorded video during the experiment and asked participants to fill out a questionnaire on their experience.

**Procedure**

Participants sat on a chair in front of the surface and were instructed how to scroll the dial. They put their index finger on the center of the hole, dragged it to the center of the left hole, and released it to increase the number of the dial. They were instructed not to flick their finger (i.e., releasing the finger before reaching the other hole).

Participants were asked to find the maximum number of the dial (i.e., the end of the dial). They dragged their finger to scroll the dial from 0 to the maximum number. When they thought the maximum number entered the box, they pushed the tact switch to complete the task. They were asked to do the task as quickly as they could.

The experiment consisted of four blocks. One feedback condition was assigned to one block. One block consisted of two sections: 1) participants practiced the task 15 times (training section); and 2) they conducted the task 15 times (testing section) with assigned feedback. The five lengths of the dials were randomly presented three times. Participants conducted all four blocks. The order of the blocks (i.e., feedback conditions) was counterbalanced within the participants. We collected the data (task completion time and error number) only from the testing sections. During the experiment, white noise was played through earphones to mask the audio cues produced by the attractive force and the vibration feedback.

After finishing four blocks, the questionnaire asked several questions, including an open question and the following five questions:

Q1 During the vibration test, did you feel the vibration at the end of the dial?
Q2 During the attractive force test, did you feel any suction force at the end of the dial?
Q3 How did the visual spring work for your task?
Q4 How did the vibration work for your task?
Q5 How did the suction force work for your task?

Q1 and Q2 were asked to investigate how often participants felt the haptic cues and to compare the VB and the AF conditions. They were answered using a five-grade Likert scale (1: not at all – 3: sometimes - 5: always). Q3, Q4, and Q5 were asked to compare the participants' preferences. They were answered using a seven-grade Likert scale (1: very poor – 4: neither good nor poor – 7: very good).

### Hypotheses

We had three hypotheses for the task:

H1 The conditions from the shortest to the longest task time are AF, VB, VS and NF.
H2 The error rate in the NF condition is greater than any other condition.
H3 The AF condition is preferable to any other condition.

We hypothesized H1 because participants that do not have haptic feedback must make at least one scroll gesture at the end of the dial to confirm it is the end, while those with haptic feedback know they have reached the end of the dial the moment they arrive. In addition, the task time in the AF condition is shorter than that in the VB condition because the AF has participants stop their fingers at the end of the dial, which allows them to move their fingers quickly toward the tact switch. On the other hand, participants can ignore or miss the VB and make an extra scroll gesture. The task time in the VS condition is shorter than that in the NF condition because it seems to be difficult for participants to confirm the end of the dial without feedback since it is hard to separate the sensor's mistakes (i.e., the touch sensor misses the scroll gesture) from the end of the dial. We predicted H2 for the same reason. As for H3, the device is easier to manipulate since a dial menu is similar to a physical dial, i.e., the finger stops along with the dial when the dial reaches the end position.

### Results

#### *Task time*

We took the median task time across three repetitions for each dial length for each participant. The mean task times for the four feedback conditions with respect to the five dial lengths are shown in Figure 9. A two-way within-participants repeated-measures analysis of variance (ANOVA) was performed on the task time data. The within-participants factors were Dial Length (L4, L6, L8, L10 and L12) and Feedback (NF, VS, VB and AF).

There were significant main effects for Dial Length ($F(4, 92) = 185.3$; $p < 0.001$) and Feedback ($F(3, 69) = 14.7$; $p < 0.001$). While multiple comparison tests (Bonferroni test) for Feedback partly support H1, there was no significance between NF and VS (AF < VB < NF = VS; $p < 0.05$; alpha level is 0.0083).

We found a marginally significant interaction effect for Dial Length × Feedback ($F(12, 276) = 1.7$; $p = 0.075$). We performed multiple comparison tests for Feedback at each Dial Length with a 0.05 significance level and a 0.0083 alpha level. At L4 and L6, there were significances other than between VB and AF and between NF and VS (i.e., there was significance between no haptic feedback and haptic feedback conditions). On the other hand, there was also no significance between NF and VB at L8, no significance between VS and VB at L10, and no significances between NF and VB or between VS and VB at L12. These results indicate that the VB helped to shorten the task time when the Dial Length was short (e.g., L4 and L6). However, the effect was reduced when the Dial Length was long (e.g., L8, L10 and L12). One possible reason for the reduction of the effect is that participants tried to repeat the scrolling gesture. Even if the vibration was present, they ignored or missed the vibration because they tried to scroll faster to reach the end of the dial when they could not find it with the initial few scrolls. This would seldom happen in AF as we expected in H1.

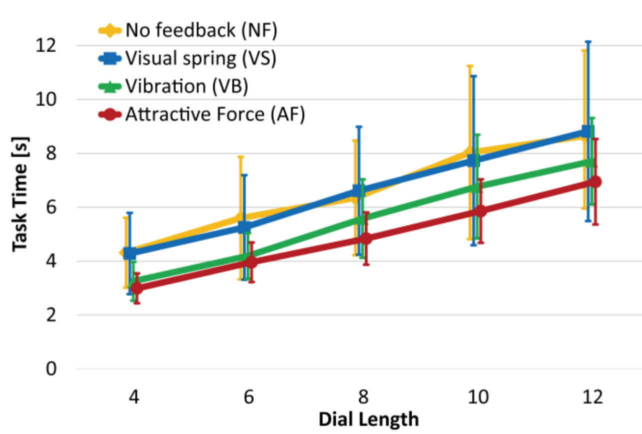


**Figure 9. Task times for the four feedback conditions (+/- standard deviation of the mean).**

*Error rate*

The error rates for NF, VS, VB and AF conditions were 3.1%, 0.3%, 1.3%, and 0.8%, respectively. A binomial logit model analysis was performed on the error rate data. The following model was applied:

$$Error \sim \alpha + \beta \times FDBK + r,$$

where *Error* is a rate of error, *FDBK* are the feedback conditions (NF, VS, VB and AF) and *r* is the random effect (participant). When NF is set as a baseline, the odds ratios of VS, VB and AF are 0.067 ($p < 0.01$), 0.411 ($p = 0.07$), and 0.202 ($p < 0.05$), respectively. Additionally, the VB condition did not reach a significant level, which partly supports H2.

*Questionnaire*

The results of the answer to Q1 and Q2 are shown in Figure 10. While a Wilcoxon signed rank test was performed on the scores, there was no significant difference between them ($p = 0.492$). The result implies that most of the participants felt haptic cues during the two haptic feedback conditions while we expected that participants would sometimes miss the vibration feedback. Thus, taking the result of task time into consideration, participants tried to make extra scrolling gestures at the end of the dial even if they felt a vibration, i.e., they seemed to ignore the vibration.

The results of the answers to Q3, Q4, and Q5 are shown in Figure 11. A Steel-Dwass test was performed on all three combinations of scores. There was significance between Q3's and Q5's scores ($t = 3.1$; $p < 0.01$). On the other hand, there were no significances between Q3's and Q4's scores ($t = 2.0$; $p = 0.11$) or between Q4's and Q5's scores ($t = 2.3$; $p = 0.06$) while they were close to the significant level. This result implies that there was a tendency for participants to prefer the attractive force feedback as expected by H3.

According to the responses to the open question, we found may positive comments for the attractive force, which also supports H3. For example, one participant reported, "Suction force was felt as if someone held my finger tip and prevented me from moving. Thus, it will be useful to control without eye focus." While similar responses were also observed for vibration, one participant mentioned, "I was not quite sure of the vibration." Another participant mentioned, "The suction force physically stopped the finger, and was so intuitive. The vibration, on the other hand, was still implicit or symbolic."

There were, on the other hand, the following responses to the open question: "Suction force was interesting, but so novel that it took times to get used to it" and "I was frightened at suction force."

## DISCUSSION

### Experimental Results

One of the most attractive aspects of VacuumTouch is its ability to affect a user's movement. In the experiment, participants were asked to make scrolling gestures in a repetitive manner. In other words, the finger was actively moving. In that case, it was difficult to stop or change its movement even if the vibration that indicated the end of the dial was provided. On the other hand, the attractive force could stop the movement. This implies that the attractive force provided by VacuumTouch had enough force to change or guide the user's movement.

Speaking of the task time results, the performance of the haptic condition was superior to no haptic feedback. This was because participants with no haptic feedback had to scroll at least once to the end of the dial for confirmation (even when the visual spring effect was provided after the end came) while haptic feedback was provided at the end of the dial the moment it was arrived at, as expected in H1. However, the natural question should be what if the visual feedback was provided at the same time as the haptic condition, e.g., the color or thickness of the last number is different from the others. We will investigate this scenario in the future, but we believe that suction force is superior to visual feedback because the suction force overcame the vibration as mentioned in the previous paragraph.

In addition, not requiring a user to hold or attach an extra device allows her to easily interact with the system. It is especially positive that the tips of her fingers are open because the user can directly touch the surface. Whereas a number of interactive haptic surfaces substitute vibration feedback for force feedback, VacuumTouch can provide a more intuitive experience, as mentioned by some of the participants in the questionnaire.

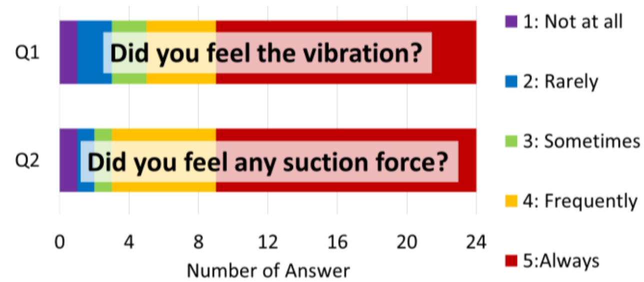


**Figure 10. Answer to Q1 and Q2.**

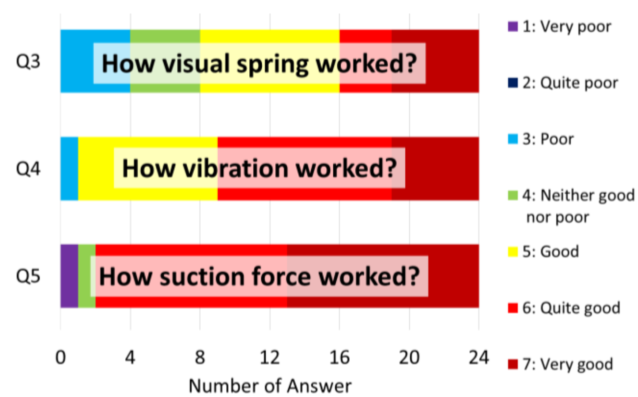


**Figure 11. Answer to Q3, Q4, and Q5.**

### Limitations and Possible Improvement

The current prototype in this study has several limitations.

The attractive force cannot be provided for a long time if the finger or hand does not completely cover the hole(s). This can be solved by using a more powerful air pump or a larger air tank to vacuum more air and keep the low-vacuum state.

The current system takes around 10ms to generate the suction force. There are two main factors to produce the latency. One is the response time of the solenoid in the air valve. The driving power of the solenoid depends on the currency. Thus, applying high voltage or using a low voltage rating solenoid are both possible solutions. The other is the air's travel time from the hole on the surface to the air tank through the air tube and air valve (flow channel, the current length is around 30cm). The solution for this is designing an appropriate air-flow channel (length and thickness of the tube) and using a more powerful pump to generate lower air pressure in the tank.

Unlike FingerFlux [35], it is difficult for VacuumTouch to provide an attractive force with the finger above the surface. The current system requires the user to touch her finger to the hole. While she feels the haptic sensation a few millimeters above the surface, the sensation is rather tactile and it is hard to say force sensation. Using a more powerful pump would possibly offer the force sensation at a longer distance. However, controlling spatial resolution (position and range of the stimulus) would still be difficult.

The current system has low-resolution and large holes, which occlude the visual image and produce unnecessary haptic cues with the edge even when the air valve is closed. A quick solution is covering the surface with a mesh screen. Another solution is to employ micro-electro-mechanical systems (MEMS) technology, such as a micro valve and microchannel. In addition, using MEMS technology allows for creating a surface including a MEMS-based touch screen [32] and MEMS-based display [4]. In addition, the VacuumTouch architecture can easily combine the attractive force to the repulsive force by using an air compressor. These implementations realize a greater variety of haptic sensations and novel applications.

### Design Considerations

A friction sensation can be modulated by modestly attracting/repulsing the finger dragged on the surface, which would be felt as if the friction of the surface increased/decreased. VacuumTouch can also be used as a high quality tactile display by applying Multi Primitive Tactile Stimulation [20]. As Makino and Shinoda have demonstrated, two different kinds of suction pressure stimulus can be induced from a sharp pin to a smooth surface tactile sensation by combining them [20].

VacuumTouch can also provide an attractive force not only with a finger, but also with any kind of object on the surface, such as a tangible input device like phycons. Moreover, a high-resolution system enables the following haptic flow applications: 1) 3D haptic displays by controlling the strength of the suction and blow according to each pixel height; and 2) vector representation by making the airflow from the blow hole to the suction hole under the finger. These applications may be useful for 3D maps and cause the user to feel the haptic flow.

## CONCLUSION

In this paper, we present a novel haptic interface architecture for a touch screen, VacuumTouch, which provides attractive force sensation without asking the user to hold or attach an additional device. VacuumTouch consists of an air pump and solenoid air valves that connect to the surface of the touch screen and suck the air above the surface where the user's finger makes contact. To assess the usability of our system as an interface, we implemented GUI applications, showing its potential effects.

With our current prototype, it is hard to say whether the applications are practical in terms of resolution. Still, we believe it is possible to realize a high-resolution suction and blow display using an air compressor and MEMS technology that enables the construction of precision (over 200dpi) 3D mechanical structures in a silicon substrate [4]. These future implementations will improve the GUI applications and enable brand-new applications.

## REFERENCES


1. Akamatsu, M. and Sato, S. A multi-modal mouse with tactile and force feedback. *International Journal of Human – Computer Studies 40*, (1994), 443 – 453.
2. Amemiya, K. and Tanaka, Y. Portable Tactile Feedback Interface Using Air Jet. In *Proc. ICAT 1999*, VRSJ (1999), 115-122.
3. Bau, O., Poupyrev, I., Israr, A. and Harrison, C. Teslatouch: electrovibration for touch surfaces. In *Proc. UIST 2010*, ACM Press (2010), 283-292.
4. Bita, I., Govil, A. and Gusev, E. Mirsol(R) – MEMS-based direct view reflective display technology. *Handbook of Visual Display Technology*, Springer (2012), 1777-1786.
5. Cardin, S., Vexo, F. and Thalmann, D. Head mounted wind. In *Proc. CASA2007* (2007), 101-108.
6. Deligiannidis, L. and Jacob, R. J. K. The VR scooter: wind and tactile feedback improve user performance. In *Proc. IEEE 3DUI 2006*, IEEE (2006), 143-150.
7. Dionisio, J. Virtual hell: a trip through the flames. *Computer Graphics and Applications 17*, 3, IEEE (1997), 11-14.
8. Follmer, S., Leithinger, D., Olwal, A., Cheng, N. and Ishii, H. Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. In *Proc. UIST 2012*, ACM Press (2012), 519-528.

9. Fukumoto, M. and Sugimura, T. Active Click: tactile feedback for touch panels. *Ext. Abstracts CHI 2001*, ACM Press (2001), 121-122.
10. Furuya, T., Yanagisawa, Y., Tamesue, T. and Itoh, K. Transmission of acoustic information of percussion instruments through tactile sensation using air-jet stimulation for hearing impaired person. In *Proc.UAHCI 2009*, Springer (2009), 48-57.
11. Gupta, S., Morris, D., Patel, N. S. and Tan, D. AirWave: non-contact haptic feedback using air vortex rings. In *Proc. UbiComp 2013*, ACM Press (2013), 1-10.
12. Hachisu, T. and Kajimoto, H. HACHIStack: dual-layer photo touch sensing for haptic and auditory tapping interaction. In *Proc. CHI 2013*, ACM Press (2013), 1411-1420.
13. Hashimoto, Y., Nakata, Y. and Kajimoto, H. Novel Tactile display for emotional tactile experience. In *Proc. ACE 2009*, ACM Press (2009), 124-131.
14. Heilig, M. Sensorama simulator. US Patent (1962) 3050870.
15. Hoshi, T., Takahashi, M., Iwamoto, T. and Shinoda, H. Non-contact tactile display based on radiation pressure of airborne ultrasound. In *IEEE Transactions on Haptics 3*, 3 (2010), 155-165.
16. Kim, Y., Kim, S., Ha, T., Oakley, I., Woo, W. and Ryu, J. Air-jet button effects in AR. In *Proc. ICAT 2006*, Springer (2006), 384-391.
17. King, C.-H., Franco, M., Culjat, M. O., Higa, A. T., Bisley, J. W., Dutson, E. and Grundfest, W. S. Fabrication and characterization of a balloon actuator array for haptic feedback in robotic surgery. *Journal of Medical Devices 2*, 4 (2008).
18. Kojima, Y., Hashimoto, Y. and Kajimoto, H. A novel wearable device to present localized sensation of wind. In *Proc. ACE 2009*, ACM Press (2009), 61-65.
19. Kulkarni, S. D., Minor, M. A., Deaver, M.W. and Pardyjak, E.R. Output feedback control of wind display in a virtual environment. In *Proc. ICRA 2007*, IEEE (2007), 832-839.
20. Makino, Y. and Shinoda, H. Suction pressure tactile display using dual temporal stimulation modes. In *Proc. SICE 2005*, IEEE (2005), 1285-1288.
21. Matoba, Y., Sato, T., Takahashi, N. and Koike, H. ClaytricSurface: an interactive surface with dynamic softness control capability. In *SIGGRAPH 2012 Emerging Technologies*, ACM Press (2012).
22. Moon, T. and Kim, G. J. Design and evaluation of a wind display for virtual reality. In *Proc. VRST 2004*, ACM Press (2004), 122-128.
23. Ng, A., Lepinski, J., Wigdor, D., Sanders, S. and Dietz, P. Designing for Low-Latency Direct-Touch Input. In *Proc. UIST 2012*, ACM Press (2012), 453-464.
24. Ohnishi, H. and Mochizuki, K. Effect of delay of feedback force on perception of elastic force: a psychophysical approach. *IEICE Transactions on Communications E90-B(1)* (2007), 12–20.
25. Okamoto, S., Konyo, M, Saga, S. and Tadokoro, S. Detectability and percpetual consequences of delayed feedback in a vibrotactile texture display. *IEEE Transaction on Haptics 2*, 2 (2009), 73-84.
26. Porquis, L. B. C., Konyo, M. and Tadokoro, S. Tactile-based torque illusion controlled by strain distributions on multi-finger contact. In *Proc. Haptics Symposium 2012*, IEEE (2012), 393-398.
27. Poupyrev, I. and S. Maruyama. Tactile interfaces for small touch screens. In *Proc. UIST 2003*, ACM Press (2003), 217-220.
28. Saga, S. and Deguchi, K. Lateral-force-based 2.5-dimensional tactile display for touch screen. In *Proc. Haptics Symposium 2012*, IEEE (2012), 15-22.
29. Sawada, E., Ida, S., Awaji, T., Morishita, K., Aruga, T., Takeichi, R., Fujii, T., Kimura, H., Nakamura, T., Furukawa, M., Shimizu, N., Tokiwa, T., Nii, H., Sugimoto, M. and Inami, M. BYU-BYU-View, a wind communication interface. In *SIGGRAPH 2007 Emerging Technologies*, ACM Press (2007).
30. Sodhi, R., Glisson, M., Poupyrev, I., Rothera, A. and Dauner, J. AIREAL: tactile gaming experinces in free air. In *SIGGRAPH 2013 Emerging Technologies*, ACM Press (2013).
31. Suzuki, Y. and Kobayashi, M. Air jet driven force feedback in virtual reality. In *Proc.IEEE Computer Graphics and Applications 25*, 1, IEEE (2006), 44-47.
32. Yoshida, S., Mizota, T. and Noma, H. Development of an integrated multi-axis tactile sensor: distributed preprocessing for tactile recognitions. In *Proc. IEEE VR 2007*, IEEE (2007), 281-282.
33. Yoshimoto, S., Hamada, Y., Tokui, T., Suetake, T., Imura, M., Kuroda, Y. and Oshiro, O. Haptic canvas: dilatant fluid based haptic interaction. In *SIGGRAPH 2010 Emerging Technologies*, ACM Press (2010).
34. Wang, D., Tuer, K., Rossi, M. and Shu, J. Haptic overlay device for flat panel touch displays. In *Proc. HAPTICS 2004*, IEEE (2004), 290.
35. Weiss, M., Wacharamanotham, C., Voelker, S., and Borchers, J. FingerFlux: near-surface haptic feedback on tabletops. In *Proc. UIST 2011*, ACM Press (2011), 615-620.