Position and Force-direction Detection for Multi-finger Electrostatic Haptic System Using a Vision-based Touch Panel

Taku Nakamura and Akio Yamamoto
Dept. of Precision Engineering
The University of Tokyo, Japan
Email: {taku_nkat, akio}@aml.t.u-tokyo.ac.jp

***Abstract*—This article proposes a method of detecting position and force-direction for multi-finger electrostatic haptic system using a vision-based touch panel. The system consists of a vision-based touch panel, a transparent ITO (Indium Tin Oxide) electrode on the panel, and multiple stimulators with markers. Analyzing positions of the markers with the vision-based touch panel, the proposed method can detect position and force-direction of each stimulator. Detection of applied force direction is imperative to reduce undesired stickiness of virtual walls in passive haptic rendering systems. The developed system could successfully reduced the stickiness, but its performance was limited due to the limited tracking performance of the touch panel.**

Keywords-Surface haptics; Visuo-haptic; Passive haptic system.

I. INTRODUCTION

Recently, multi-finger interaction on flat panel displays has been a hot topic in computer-human interaction. Many mobile devices and personal computers are now equipped with touch panels that allow user operations on their screens using multiple fingers. However, these devices do not fully exploit their multi-touch feature for information output, since they do not have haptic feedback. There are some systems that can provide haptic feedback on a flat panel display, such as electro-tactile display [1]–[3], string-based stimulator [4] and electromagnetic actuation [5], which however can provide stimuli to a single finger alone; rendering independent stimulus to multiple fingers have not been realized.

To realize haptic feedback to multiple fingers on a flat panel display, we have proposed on-screen multi-finger haptic feedback systems in [6] and [7], based on indirect electrostatic stimulation. The system requires only a transparent electrode on a visual screen and multiple stimulator pads attached to user's fingers for generating force feedback, and thus can be easily integrated onto a flat panel display. It presents passive (resistive) force feedback by friction force which is modulated by electrostatic attraction force between the transparent electrode and the stimulator pads. Applying different voltages to different stimulators provides independent stimulus to the multiple fingers.

The first prototype reported in [6] realized two independent haptic stimuli up to approximately 1 N on an LCD (Liquid Crystal Display) monitor. In that prototype, the positions of the fingers were detected using an over-mounted camera. Besides position detection, the system requires a force-direction sensor to solve "sticky wall" problem, which is commonly found in passive haptic systems [8], [9]. Our second prototype in [7] incorporated a simple force-direction sensor in the stimulator pads, which successfully reduced the stickiness of virtual walls.

Although those prototypes have successfully demonstrated multi-finger haptic feedback on flat panel displays, the systems relied on the overhead cameras, which tends to complicate the system structure; they should preferably be integrated with multi-touch input interfaces. Unfortunately, the indirect electrostatic stimulation is not yet compatible with typical capacitive-type touch interfaces, and thus other touch input principles need to be investigated for the integration. In this paper, we focus on the vision-based touch panel technology and investigate its compatibility with the multi-finger haptic feedback technology. Since both technologies, vision-based touch panel and multi-finger haptic technology, are designed for large-size displays, their integration is expected to realize rich user experience on a large-size tabletop display.

This paper is structured as follows. Section II reviews related studies on electrostatic haptic feedback. Section III explains the concept of the proposed method to realize position and force-direction detection. Section IV investigates the compatibility of the electrostatic haptic system with the vision-based touch panel, using SAMSUNG SUR40 with Microsoft PixelSense as an example. Section V discusses the design of the stimulator pad for force-direction detection. Section VI demonstrates multi-finger visuo-haptic interactions with the developed system and evaluates the performance of the force-direction detection in haptic rendering. Section VII concludes the paper.

II. RELATED STUDIES ON ELECTROSTATIC HAPTIC FEEDBACK

The multi-finger electrostatic haptic system described in this article utilizes indirect-type electrostatic stimulation. Electrostatic stimulation (or electrotactile stimulation/vibration), which was firstly reported in [10], utilizes friction force modulated by electrostatic force between two conductive objects facing each other. Using a transparent electrode as one of the two objects, haptic feedback can be realized on visual displays without impeding the visual information on the screen [1]–[3].

There are two types in electrostatic stimulation: direct and indirect. Direct-type system stimulates a finger by inducing electrostatic force between a finger and a transparent electrode on a display [1], [2]. It can render haptic feedback directly on the user's finger with a considerably simple setup. The system, however, requires segmented electrodes if we want to

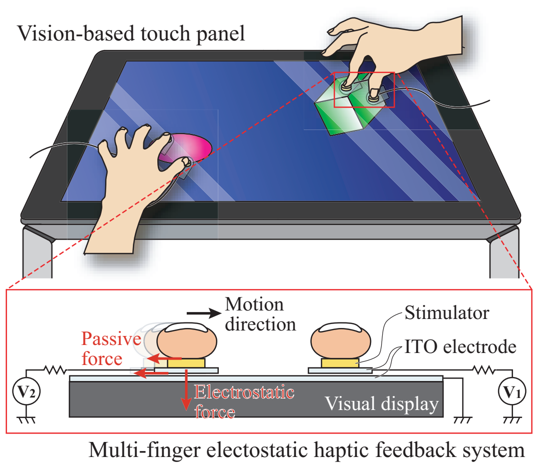


Figure 1: System overview of proposed system

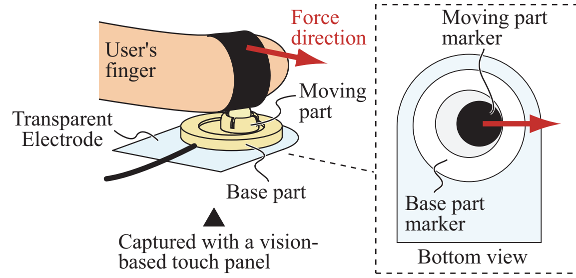


Figure 2: Concept of stimulator and marker equipped to its bottom

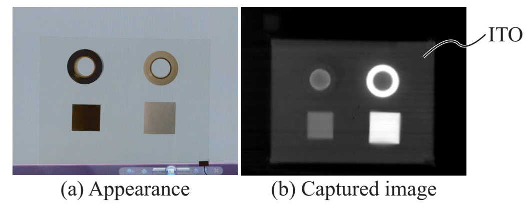


Figure 3: Appearance (a) and captured image (b) of objects on ITO film

realize multi-touch interaction, which is practically not easy to develop. Moreover, the presented force is prone to instability due to finger perspiration [11] and can provide only weak force (approximately 0.1 N as reported in [12]). Due to the small feedback force, the system can only render surface texture sensations in cutaneous sense.

On the other hand, indirect-type system stimulates a finger through a stimulator pad, which results in larger and more stable feedback force [3]. It can be easily extended for multi-touch by employing multiple stimulator pads and applying different voltages to different stimulators [6]. One drawback of the indirect type is that the stimulator pads need to be arranged on the display, which results in more complicated system structure than the direct-type. Due to this drawback, the indirect type would not be suitable for mobile devices, such as smartphones and tablets. Indirect type is rather suitable for large-size tabletop systems, to enhance user interaction on those systems.

III. Multi-Finger Haptics on a Vision-Based Touch Panel System

A. Prototype Overview

Figure 1 shows the overview of the prototype system that was studied in this paper. The system integrates multi-finger electrostatic haptic feedback system as proposed in [6] on a vision-based touch panel PC (Samsung SUR40 with Microsoft PixelSense). The novelty of this work compared to the previous studies in [6], [7] is to utilize the touch panel for positions and force-directions detection, which can considerably simplify the setup. The touch panel contains IR (infrared) backlight and IR sensor array inside the LCD panel, with which the system detects the object locations on the screen. In the integrated prototype, the touch panel detects the positions of the stimulator pads, as well as applied force directions on the pads. The system then calculates feedback force based on the interaction within the visually-rendered virtual world, which is then provided to the pads such that the user can haptically feel the virtual world through their multiple fingers.

The multi-finger electrostatic haptic feedback system consists of a non-segmented transparent electrode that covers the whole surface of the display and multiple stimulator pads. A user is equipped with those pads on his/her fingertips to receive haptic stimulus. The transparent electrode is electrically grounded, and each stimulator pad is fed voltage through a voltage feeding wire. The voltage application to the pad changes vertical electrostatic attraction force between the pad and the display. The motion of the fingertip, then, converts the attraction force into horizontal friction force, which is perceived as haptic stimuli. Without fingertip motion nor putting the fingers on the pads, no feedback is given to the user. By applying different voltages to different stimulator pads, the pads can render different stimuli simultaneously.

B. Position and Force-Direction Sensing

Detection of position and applied force direction is realized by analyzing a captured IR image taken by the vision-based touch panel. The position means positions of stimulator pads, and the applied force direction is detected by using relative displacement of a user's finger to the stimulator pad attached to the finger. Figure 2 shows the concept of the structure of the stimulator pads that realizes the detection. Each stimulator pad consists of a base part and a moving part which the user wears on his/her fingertip. The base part is connected to a transparent electrode, to which the voltage for electrostatic stimulation is applied. The base part is ring-shaped and is marked in white on its bottom. The moving part, which is marked in black on its bottom, can be moved freely by a user within the inner circle of the base part. The system detects the position of the stimulator by calculating the center position of the white marker and force direction by comparing the black marker position against the white marker.

IV. Design Consideration

A. Interference of ITO Film to Vision-based Touch Panel

The applicability of ITO electrode to the vision-based touch panel using IR sensors is investigated in this section. As the ITO transparent electrode is not perfectly transparent in infrared region, its effect on the vision-based touch panel needs to be investigated. To examine the interference, some IR images were captured through a small ITO film. Figure 3 shows one of the captured images. In this image, the ITO film covers the rectangular area, on which some objects are placed. The objects are two sheets of black/white paper and two rolls

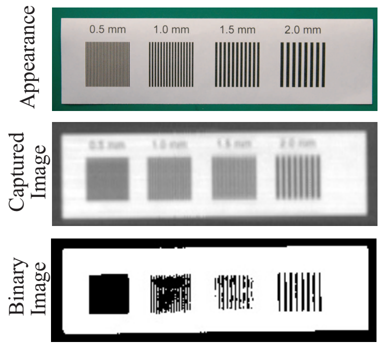


Figure 4: Appearance (top), captured image (middle), and binary image (bottom) of striped pattern

of black/white vinyl tape. The image shows that the ITO is not perfectly transparent in the IR region, but is transparent enough for object detection.

It was confirmed that the black vinyl tape completely absorbed the IR light, and thus invisible, whereas the white paper and vinyl tape were clearly visible even through the ITO film. The black paper sheet did not provide clear image, and thus is not suitable as a marker. In addition, an interesting phenomenon was observed. In the captured image, the inside of the black vinyl tape roll appears bright, although there is nothing inside. That is probably because IR light was reflected on the inside of the roll, whose color was white. It shows that the captured image is affected not only by the bottom color of the objects, but also by the vertical edge faces, suggesting that the color of edge faces should be designed carefully when making the stimulator pads.

B. Resolution of Captured Image

The resolution of the captured images through the ITO film was investigated, as the resolution is important to design marker pattern for the stimulator pads. According to the specification of the display, the display size is 885.6 × 498.15 mm and the captured image has 960 × 540 pixels, which means the pixel resolution is approximately 1 mm. However, the IR image can be blurred and practical resolution can be much worse.

To evaluate the resolution, some black striped patterns printed on white paper were observed through an ITO film. Four different stripe patterns were prepared, with different widths for black strips: 0.5, 1.0, 1.5, and 2.0 mm. The white strips had the same width as the black strips. Figure 4 shows their appearance, a captured image on the touch panel, and a binarized image. Although the boundaries of the striped patterns are blurred in the captured image, all the stripes except 0.5-mm interval were recognized as stripes even in the binary image. This pilot evaluation indicates the system can recognize 1.0 mm object through the ITO film.

C. Latency of the vision-based touch panel

The latency of the vision-based touch panel in position detection was measured. A white marker was moved laterally on the touch panel, whose position was measured by both the touch panel and a laser displacement sensor (OMRON, ZX-LD100). Figure 5 compares the measurement results. The red dashed line indicates the reference position measured with the laser sensor. The blue line indicates the position detected by

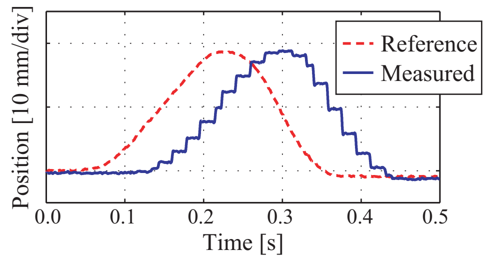


Figure 5: Latency of the vision-based touch panel in position detection.

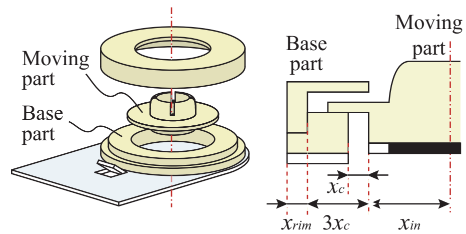


Figure 6: Assembly diagram (left) and cross section (right) of stimulator pad

the touch panel. The latency of the touch panel in position detection was found to be about 80 ms.

The latency limits the maximum motion speed for proper operation on the electrostatic haptic system. If we suppose 4-mm tolerance for position detection, the maximum speed is limited to 0.05 m/s for the latency of 80 ms. The speed is much smaller than a desired speed: e.g. 0.5 m/s, which was realized in the previous tracking system in [7] using an overhead motion-tracking camera, which has 8-ms latency. The desired speed could be achieved by compensating the latency with some kind of predictive control, which would be implemented in our future work.

V. Force-Direction Detecting

A. Design of Stimulator Pad and Its Marker

Figure 6 shows the assembly diagram and cross sectional view of the proposed stimulator pad to facilitate force-direction detection, as well as position detection. The stimulator pad consists of a base part fixed on a small ITO electrode and a moving part fixed to a user's finger. The base part has a cap to prevent the moving part from popping out from the base part. The proposed system calculates the applied force direction by detecting relative displacement of the moving part to the base part. Thus, it requires large clearance for accurate detection of force-direction. According to the resolution of captured image, the clearance must be larger than 1.0 mm. The accuracy of force-direction detection is expected to be higher as the clearance becomes larger. However, large clearance enlarges the size of stimulator pad, in trade-off. As shown in Figure 6, the radius of the stimulator r becomes $r = x_{rim} + 3x_c + x_{in}$, where x_{rim} is the width of the cap part, x_c is the clearance between the base and moving part, and x_{in} is the radius of the marker for the moving part.

We determined the size so that the width of the stimulator pad becomes comparable to the width of human finger, to avoid occlusion of visual information. Figure 7 shows the appearance of prototype stimulator pads. Two stimulator pads with different design parameters were prepared for evaluation: the smaller one has 1.0 mm clearance and its diameter is 16

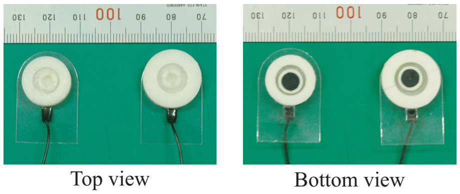


Figure 7: Appearance of stimulator. Top view (left) and bottom view (right)

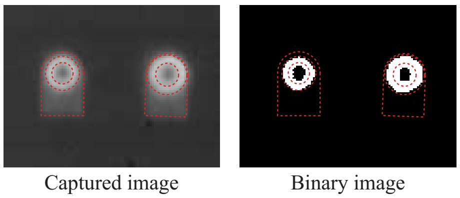


Figure 8: Captured image (left) and binary image (right) of prototype stimulator on the vision-based touch panel

mm, and the larger one has 1.5 mm clearance and its diameter is 19 mm. They have common width of the cap (1 mm) and radius of the moving part marker (4 mm). To obtain high contrast images at the border between the black and the white marker, a black circle marker (ϕ6 mm) enclosed by white ring (1 mm width) is attached to the bottom of the moving part.

Figure 8 shows a captured IR image and a binarized one for the two stimulator pads placed on the touch panel covered with the ITO film. Red dashed lines in the figure indicate the contours of the stimulator electrodes and those of the base-part markers. The clearance between the base part and the moving part is blurred in the captured image and not clearly visible. Yet, the black marker on the moving part is clearly observed as a black circle, and thus it is expected that the force direction can be calculated from the relative position between the black circle and surrounding white circle, for both prototype pads.

B. Evaluation

The force-direction detection capability was evaluated for the two prototypes in a static condition. The stimulators were fixed on the touch panel displaying no visual image, and their moving part was pushed to 8 directions in every 45°. The force-direction (which is pushed direction) was calculated from the relative position of the markers. Then, the mean, maximum, and minimum values of detected direction for two seconds in every direction were measured. Figure 9 and Figure 10 show the results for the smaller prototype and the larger prototype, respectively. Both prototypes succeeded in detection, but their resolutions are considerably different. The smaller prototype showed an error up to approximately 45°, while the larger prototype indicated an error up to approximately 15°. It confirms that the larger clearance increases the accuracy of the force-direction detecting, as expected.

Although the above static evaluation was conducted on the black screen, if there is some visual image displayed on the screen, it can influence the performance of force-direction detection. An example of such influence is shown in Figure 11. When the stimulator pad is placed on the border of black and white image as shown in Figure 11(a), the touch panel captures a distorted image of the marker as the images on the display is reflected by the ITO film and the makers, as in Figure 11(b). In this case, the system cannot detect the force-direction correctly,

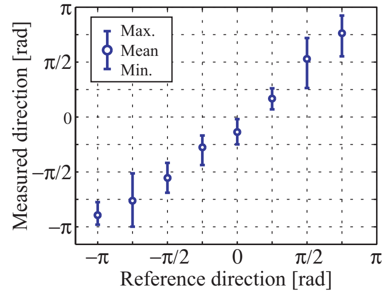


Figure 9: Results of force-direction detecting of small clearance pad

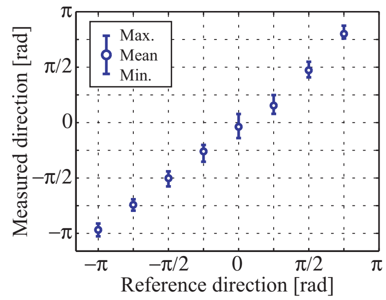


Figure 10: Results of force-direction detecting of large clearance pad

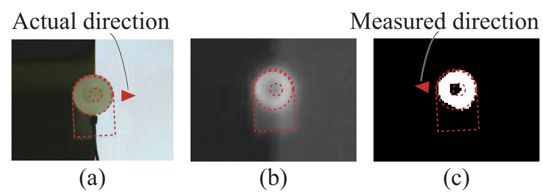


Figure 11: Failure case of force-direction detecting. Appearance (a), captured image (b), and binary image (c) of stimulator at the border on black and white background.

as shown in Figure 11(c) that shows completely opposite force direction.

There are two possible approaches to solve this problem. One is to fix the image under the stimulator. By tracking the stimulator position and drawing a constant-colored background below the stimulator, the system can fix the condition for force-direction detection. This approach, however, limits the motion speed of the stimulator pad quite low, since the position tracking speed of the touch panel is not so fast in this system.

The other is to render virtual environments in low contrast colors. Using colors which are captured in similar brightness, such like black and blue, the system can reduce the marker distortion, even when the stimulator pad is placed on a border between different colors. This approach limits coloration of virtual environments, but it is not affected by the tracking speed. In the final experiment described in section VI-B, we adopted this latter approach.

To evaluate the dynamic performance, the response time was measured with the large-clearance stimulator. The response time, or latency, of the force-direction detection was found to be about 80 ms, which is almost the same as the latency of the touch panel.

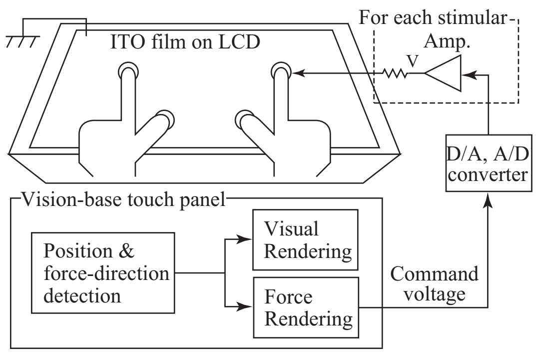
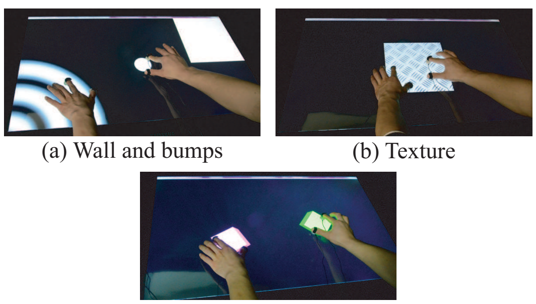


Figure 12: Prototype setup



(a) Wall and bumps (b) Texture

(c) Dynamically moving cubes

Figure 13: Examples of multi-finger visuo-haptic interaction

VI. Pilot Experiment for Haptic Rendering

A. Demonstrations without force-direction detection

Figure 12 shows the setup of the whole experimental system. The system consists of the SUR40, whose surface is covered with a transparent ITO electrode, four stimulator pads, a DA/AD converter board, and four high-voltage amplifiers. The ITO electrode was grounded electrically, and its surface was insulated with a PET film (8 μm in thickness). The four stimulator pads are the larger one of the two types discussed. The bottom surface of stimulator ITO electrode was also covered with the PET film.

In [6] and [7], rendering of static objects, such as walls, bumps, and surface textures, as well as dynamically moving objects, were reported. First, the same interactions have been implemented, but without force-direction detection, on the developed system as shown in Figure 13. In these interactions, the rendering program runs at approximately 80 Hz. When the system did not employ the force-direction detection, if we ignore the sticky wall and object stiction [7] problems, the system could successfully render the haptic reaction force, although the maximum operation speed of the contact pads was limited to several centimeters per second for proper operation. This limitation was due to the low sampling rate and the latency of the touch panel.

B. Evaluation of Force-Direction Detection in Wall Rendering

In a passive haptic rendering, a surface of a static virtual wall can be felt sticky. This stickiness comes from the fact that passive friction force always acts toward the opposite direction of user's motion. Typically, a virtual wall is described as a spring; if a contact point is penetrating the surface, a force proportional to the penetration depth is fed back, which should be directed toward outward direction. When the contact pad is proceeding into the wall, there is no problem as the reaction force is in the opposite direction of the moving direction. On the other hand, when retreating, the force direction and the moving direction are the same, which is not possible to realize on a passive system.

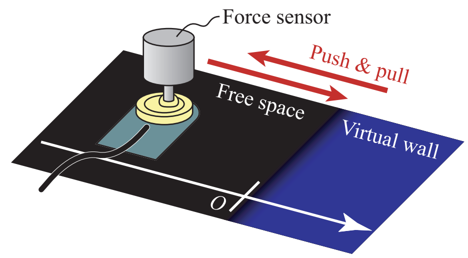


Figure 14: Setup of virtual wall rendering evaluation

Typical solution for this is to cut the force rendering during retreating. To facilitate that, the system needs to detect in which direction the user is trying to move the contact pad. In the developed system, the direction of the applied force is achieved by the force-direction detection mentioned above. Thus, the following evaluates if the force-direction detection method can successfully eliminate the sticky wall problem.

The schematic illustration of the experimental setup dedicated for the purpose is shown in Figure 14. In this setup, only one pad was used whose motion is limited in one-dimension by using a linear guide. The stimulator was manually moved to enter into and retreat from a virtual wall, during which the rendered force was measured with a force sensor (Nitta, PD3-32). Virtual wall was visually rendered using blue color on black background to prevent the malfunctioning of the force detection, as mentioned before.

Figure 15 shows the result of virtual wall rendering, first without considering force direction. The plot on the top shows the center position (solid line in the top) and the both edges (dashed line in the top) of the stimulator pad, calculated from the IR captured image. The penetration depth was calculated using the edge position. The other two plots are for the applied voltage and the measured force. When the stimulator pad hits and pushed on the wall (the first half of the plots), the reaction force from the wall was rendered correctly. However, in the latter half, force is exerted in negative direction while the operator was trying to retreat from the surface. This means that the contact pad is sticking to the virtual wall.

Figure 16 shows the result of virtual wall rendering that considered applied force direction. The former half is almost the same as the previous experiment, but the latter half shows the distinct difference. As the force direction was altered, the applied voltage was cut to zero, which allowed the stimulation pad to retreat from the virtual wall easily. Although, some negative force was observed, its magnitude and duration was considerably reduced, which confirmed the effectiveness of the proposed system.

C. Discussion

First of all, the most significant problem in the current system is the limited operation speed. In all the experiments, the operation speed of the stimulation pads was limited up to several centimeters per seconds for proper operations. This is due to the limited tracking performance of the touch panel.

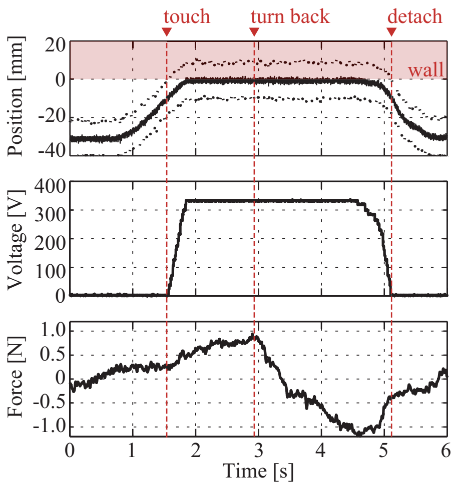


Figure 15: Result of virtual wall rendering without force-direction

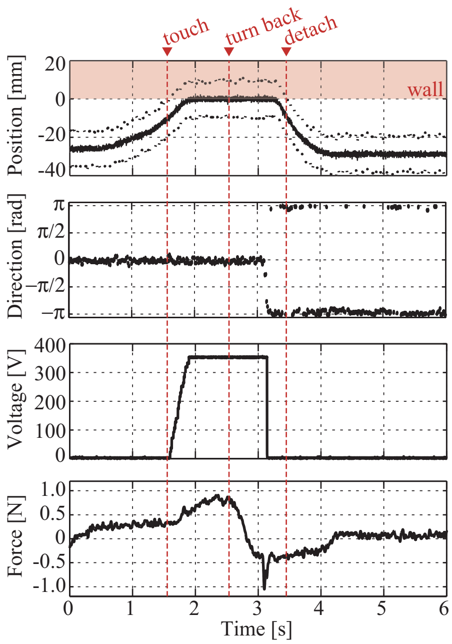


Figure 16: Result of virtual wall rendering with force-direction

For force-direction detection on a virtual wall, two major problems were found. One is vibration during detaching (which is not observed in Figure 16). As the force-direction detection is not robust enough, it sometimes outputs wrong direction. If the detection malfunctions during detaching from a wall, it results in rapid on and off of the voltage that creates vibrative sensation. This would be solved by having a dead zone in force-direction detection and to use low pass filtering in the detection result.

The other problem was the negative spike in rendering force when the user changed the force direction (which is clearly observed in Figure 16). This negative spike would be the result of the latency of the information processing. As there is time-lag between the real motion and the image capturing, the voltage was not instantly switched off as the user alters the force direction. If a user rapidly alters the force direction, the time-lag of voltage-off results in the spike of the rendered force.

The first and the third problems are both due to the processing speed of the touch panel. The problems might be solved by implementing some kind of predictive control, which we would like to work on in our future study.

VII. Conclusion

This article described position and force-direction detection using a vision-based touch panel, for multi-finger electrostatic surface haptic system. Using the embedded IR capturing system in the touch panel, the system can detect the positions and applied force directions of the stimulator pads, without relying on an overhead camera.

The paper investigated compatibility of the vision-based touch panel with the electrostatic stimulation, based on which a prototype system was designed and demonstrated. The prototype realized various visuo-haptic interactions, but the motion speed was limited due to the slow tracking speed of the touch panel. The system demonstrated successful force-direction detection, but at the same time, some limitations have become clear, which are the vulnerability against visual images and slow detection speed due to the slow tracking speed.

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