Interaction with Real Objects and Visual Images on a Flat Panel Display using Three-DOF Transparent Electrostatic Induction Actuators

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***Abstract*—This paper describes a new type of computer-user interactions through an actuated real object and visual images on a liquid crystal display (LCD). The interactions are realized by three degrees-of-freedom (three-DOF) transparent electrostatic induction actuators placed on the display. The dynamic interaction was realized using asynchronous driving characteristics of the induction actuator. The actuator does not interfere with visual images on the screen because of the optical transparency of the actuator. The actuator is equipped with eight sets of one-DOF actuators, which enables three-DOF driving, XY translation and rotation, of sheet objects. Fundamental performances of the actuator regarding the 3-DOF motions are investigated. Also, a prototype interactive application is demonstrated.**

***Keywords*-electrostatic actuator; transparent; three-DOF; visual interaction;**

I. INTRODUCTION

Recent progress of information technologies have provided us with many digital contents. In the use of the digital contents, user interfaces have been given an important role to determine user experiences. In the days when pointing devices and keyboards were principal input devices, touch panel screens enhanced user experiences by giving intuitive interaction with computers. While their use of touch modality is limited for manipulation of digital graphics, other trials of using real tangible objects for communication modality have also been studied [1–4]. In such interactions, users can communicate with computers intuitively by touching, moving, and picking up the real objects. This intuitive interaction will be further enhanced by returning responses to the real objects by actuating them based on the digital data, which requires embedded actuators. Most of the actuators used for such interaction systems are electro-magnetic actuators. Although electromagnetic actuators have high output forces and high controllability, they typically have heavy and bulky structures.

Recently, an electrostatic actuator has been introduced in this field as an alternative actuator [5–7]. The electrostatic actuator is a thin and lightweight actuator, which can directly drive a sheet-type object placed on it [8]. In addition, it can be manufactured in transparent color by means of transparent conductive materials, such as indium tin oxide (ITO). Since it does not occlude the images on a LCD display, combinations of the actuators and LCD displays have successfully demonstrated interactions with a real tangible object and virtual images, with considerably simple system setups.

The electrostatic actuators that were incorporated in those systems can be divided into two different types: asynchronous and synchronous types. As discussed more in detail in the next section, due to their different characteristics the suitable applications are also different. Asynchronous type is suitable for dynamic user interaction, whereas synchronous type is suitable for rather static one. For synchronous type, two-DOF motions have been demonstrated for active tangible systems [7], [9]. On the other hand, for asynchronous type, only one-DOF actuator has been introduced for active tangible systems, although three-DOF motion was already investigated for this actuator, apart from active tangible systems [10].

In this paper, a transparent electrostatic asynchronous actuator to realize three-DOF motion is reported and applied for an active tangible system. The system utilizes pen-tablet digitizer to detect the motion of an actuated sheet. With the help of the digitizer and the actuator, the system realizes intuitive interaction with computer animation through a sheet-like tangible object.

Section II compares two different driving characteristics of the electrostatic actuators from the viewpoints of interactive systems. Section III introduces the basic driving principle of an electrostatic actuator. Section IV describes the structure and features of fabricated transparent 3-DOF electrostatic actuator. Section V evaluates the actuator experimentally. Section VI proposes active tangible interaction system using the actuator. Section VII concludes this paper.

II. ELECTROSTATIC ACTUATORS FOR INTERACTIVE SYSTEMS

Electrostatic actuators have several types of driving methods, which provide different characteristics of slider behavior. According to the interactive systems, we can classify them into two different types based on their driving characteristics: synchronous and asynchronous. In the synchronous type, the displacement of the actuated object is determined by driving signal. In the case of the synchronous electrostatic motor [7], [9], the displacement or speed of the object is in proportional relationship with the phase or frequency of the driving ac signals. This facilitates positioning of the object in open-loop control without any external sensors. By changing phase or frequency, the system can easily control the position or the speed of the object. However, when subject to too large external forces (which means overloading), synchronous actuators typically "step-out". If the external load is too large such that the actuator cannot keep the designated object displacement

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TABLE I: FEATURES OF TWO DIFFERENT ACTUATION PRINCIPLES

Driving motion	Synchronous	Asynchronous
Position control	Available in open-loop control	Requiring Sensor feedback
Behavior in overloading	step-out and causes vibration	smooth motion without step-out
Suitable application	Applications requiring relatively accurate positioning	Dynamic interaction between users and tangible objects

anymore, the object will jump to some other point, which is called step-out. When an actuator steps-out, the object shows vibrating behaviors because of the jumping, which can be felt unpleasant if it is used in an interactive system.

In an asynchronous type, the driving force is determined by driving signal. The displacement of the object has no direct relation with the driving signal. Thus, for displacement or speed control, sensor feedback is necessary. On the other hand, there is no "step-out" in asynchronous actuator since asynchronous operation does not define the displacement. If there is too much external force, the object will be simply pushed back without distinct vibrations.

The two different actuation principles features are summarized in Table I. Due to their different characteristics, they can be used in different interactive applications. A synchronous type would be more suitable for applications that require position control. For example, the application demonstrated in [7] fully exploited the feature of the synchronous actuator. It realizes synchronous motions of computer animation and a tangible object, without any external sensors.

An asynchronous type would be rather suitable for applications requiring dynamic interaction. Here, "dynamic interaction" means that a user continuously moves the object to interact with some computer graphics. In [5], [6], such interactions have been demonstrated where a user can play a game of catch with a computer animation. In this application, the asynchronous behavior was imperative, as the user pushes back a ball against actuator's operation. If a synchronous actuator was utilized, the user would have felt unpleasant vibrations.

In this work, we focus on asynchronous actuator and develop 3-DOF version to realize more dexterous interaction than those demonstrated in [5], [6].

III. BASIC PRINCIPLE OF ELECTROSTATIC ACTUATOR

The three-DOF actuator used in this paper combines several one-DOF actuators. Thus, the basic structure and principle of one-DOF actuator is explained first. Fig. 1 illustrates the basic structure. It has a sheet with embedded electrodes, which is called "stator", and a sheet object that is to be actuated. The slider electrodes are connected into three phases so that three-phase ac voltage can be applied. The actuated object is a dielectric material without any electrode inside. A paper sheet or a plastic sheet is available as the actuated object.

Applying ac voltages to the stator electrode generates traveling voltage wave on the stator, which induces traveling electric charge wave on the slider, as shown in Fig. 1. The electrostatic interaction between the two traveling waves provides horizontal actuating force. As the electrostatic interaction also provides vertical attraction force, the friction between the actuated object and the stator must be kept low enough.

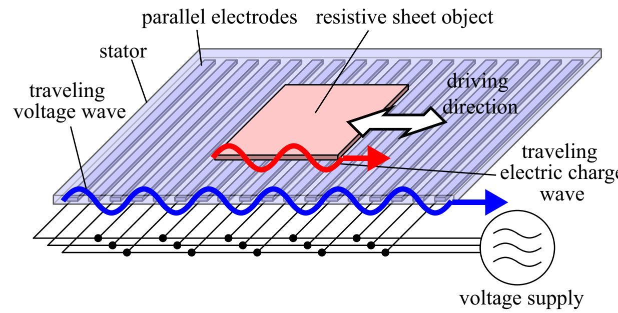

Figure 1: Schematic diagram of a one-DOF electrostatic actuator.

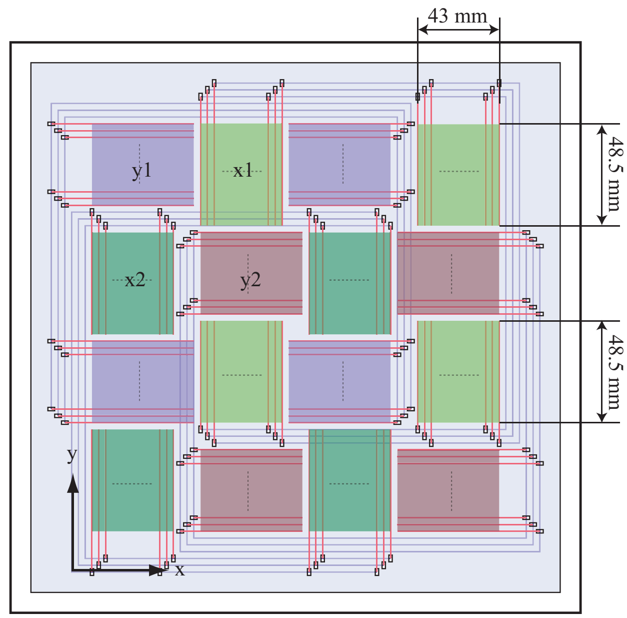

Figure 2: Structure of a 3-DOF actuator designed using combination of 1-DOF electrodes of X or Y.

IV. TRANSPARENT THREE-DOF ACTUATOR

A. Structure

This section describes a transparent three-DOF electrostatic actuator, which can realize XY translation motion and rotating motion of a slider. The three-DOF actuator is designed by tiling multiple one-DOF actuators in a checkerboard pattern. Fig. 2 shows the design of the electrodes, which has a four-by-four tiling structure. The units in the same color are connected to the same bus lines, and thus will be activated with the same voltage patterns. Fig. 3 shows driving methods for translations. One half of the electrodes produce X-direction force and the others produce Y-direction force. Using either one of the electrode groups, one can drive a slider in an X or Y translational motion. Diagonal motion can be available using both of them. The direction of the translation can be changed by exchanging any two of the three phases of the voltages, which reverses the traveling direction of the voltage wave.

Rotating motion can be produced using a combination of four electrodes, as shown in Fig. 4. Rotating can be realized only on limited points. As shown in a later section, possible rotating direction is fixed for each point due to the electrode structure. The rotation toward the other direction is not stable. Fig. 5 shows the available rotating points and their stable

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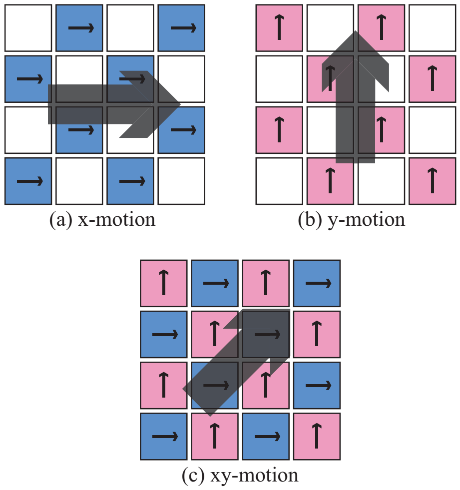


Figure 3: Driving method for X, Y, and diagonal translations.

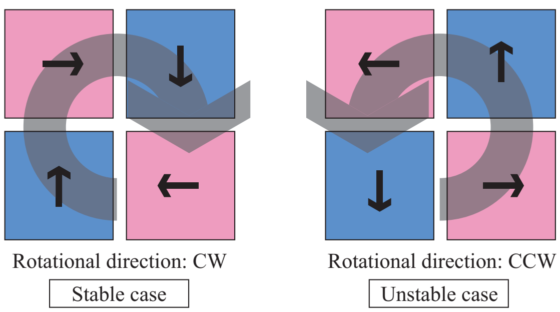


Figure 4: Driving method for rotation. (Left) stable and (Right) unstable rotation in a rotating point.

rotating directions. Four points have clockwise (CW) rotating direction and the others have a counter-clockwise (CCW) rotating direction.

This rotating motion is unique to this asynchronous actuator; it is not possible with the two-DOF synchronous actuator reported in [7] as the synchronous actuator requires the electrodes within an actuated object to always be parallel to the stator electrodes.

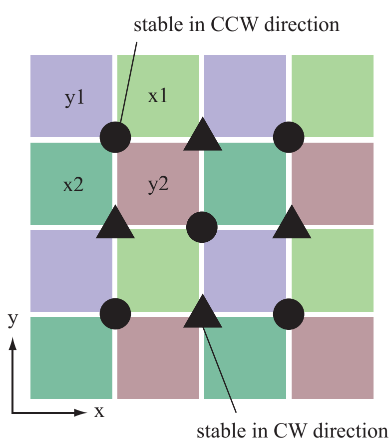


Figure 5: Available stable clockwise (CW) or counter-clockwise (CCW) rotations in a 3-DOF electrode.

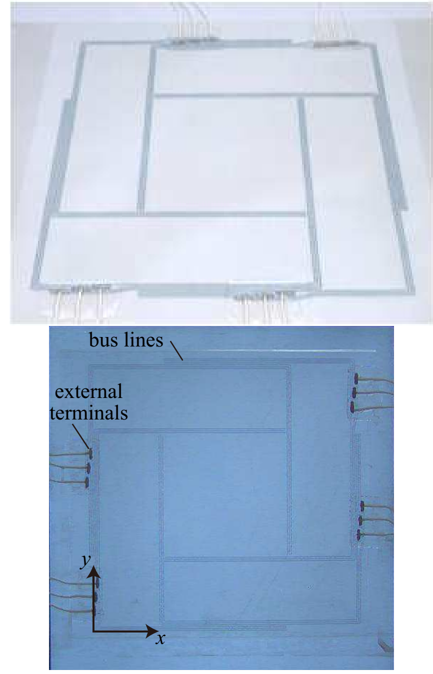


Figure 6: Photo of a 3-DOF transparent electrostatic actuator (upper) and its appearance on an LCD display (lower).

B. Fabrication

Fig. 6 shows the transparent 3-DOF actuator that was developed in this work. The actuator has transparent ITO electrodes on polyethylene terephthalate (PET) sheet, which is also transparent [6]. Although the main actuating electrodes are transparent ITO, bus lines, which connect the actuating electrodes into three phases, are not perfectly transparent as it is made of conductive polymer ink; it has pale blue color.

In the fabrication of the actuator, three-phase actuating electrodes were fabricated on a PET sheet by etching. Then, they were covered with insulating ink except for through-hole positions by screen-printing. Next, bus lines were printed over the through-holes to obtain electrical connection with the actuating electrodes. Finally, all of the electrodes were covered with insulating ink again except for electric terminals that connect to voltage sources.

The pitch of the actuating electrodes is 1.0 mm with line/space width of 0.7/0.3 mm. Size of each one-DOF electrode measures 48.5 by 43 mm.

V. EXPERIMENTAL EVALUATION OF ACTUATOR

This section evaluates slider motions on the developed 3-DOF electrostatic actuator. A polyethylene sheet with a thickness of 0.1 mm and square size of 90 mm was used as an actuated object. Fig. 7 shows a photo of the sheet and the condition for position detection. The sheet has printed markers with a diameter of 10 mm, at the center and the four corners.

Motion of the actuated sheet was measured using motion analyzing microscope (VM-6000, Keyence Corp.). The frame rate was 250 fps. Applied voltages were generated from waveform generator (7075, Hioki E. E. Corp.) and amplified thousand-fold using high voltage amplifiers (Model 609C-6, TReK Inc.). Applied voltage was three-phase sinusoidal waves with amplitude of 600 V_{0-p}. Glass beads with diameter of 100 μm were scattered between the stator and a slider

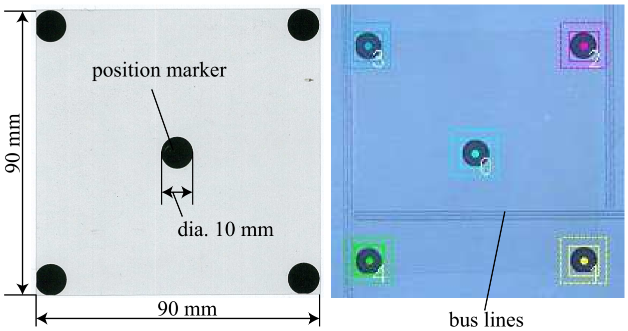


Figure 7: An example of a slider with size of 90mm square used for motion evaluations.

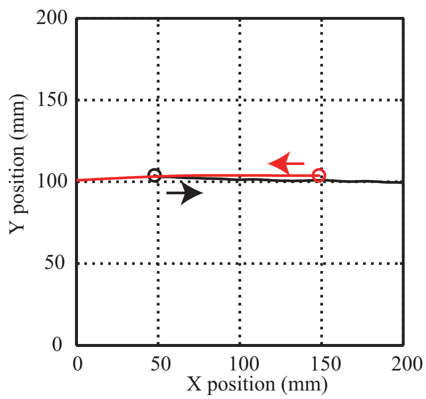


Figure 8: Bidirectional X motion of a 90 square -sized slider.

to reduce friction. First, translational motion along X axis was investigated. Changing the applied voltages realized a bidirectional X motion, as shown in Fig. 8. Similarly, Y motions were evaluated using the same slider. Fig. 9 shows the results of Y motions. Diagonal motions were also evaluated by exiting both X and Y electrodes. Trajectories of the slider for the diagonal motion are shown in Fig. 10. These results showed that sliders can be actuated in any directions.

Next, rotating motions were evaluated. The slider was placed on the center of the three-DOF electrode. Two directions of rotation were evaluated, as shown in Fig. 11. Fig. 11(a) showed a stable CCW rotation at the center point. In

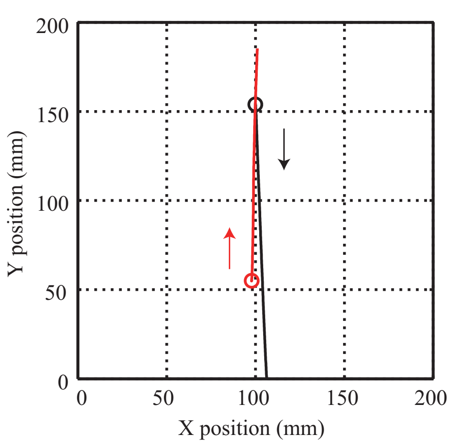


Figure 9: Bidirectional Y motion of a 90 square -sized slider.

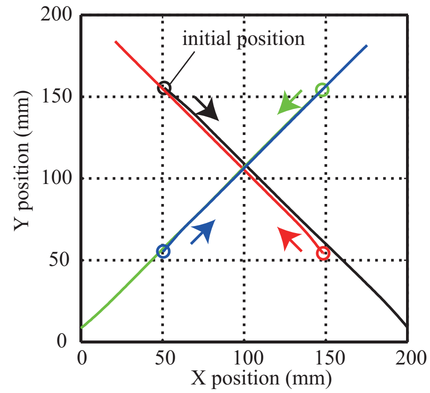


Figure 10: Diagonal motion of a 90 square -sized slider with four directions

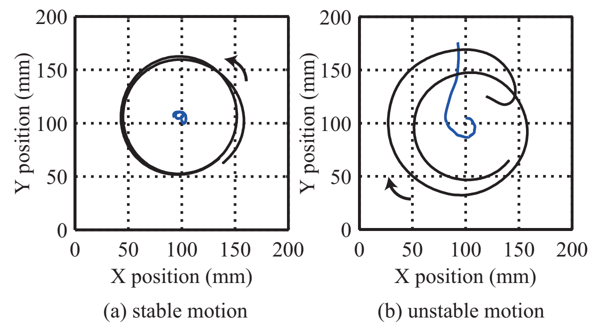


Figure 11: A stable motions and an unstable motion in a rotating point. (a)a stable CCW rotation. (b)an unstable motion

contrast, the CW motion failed in a short time, as shown in Fig. 11(b). The cause of the failure is outward force direction. When the sheet was rotated in CCW direction, all the four sets of the actuating electrodes generate inward forces, which keep the sheet at the rotation point. On the other hand, when CW rotation was tried, all the four electrode sets produce outward forces, in such a case, the rotation point is unstable equilibrium for the sheet.

Through these results, we confirmed that the newly designed 3-DOF actuator can provide quasi 3-DOF motion, which are X and Y translation and rotation at selected points.

VI. ACTIVE TANGIBLE INTERACTION SYSTEM

A. System overview

Finally, a tangible interaction system was prototyped by placing the 3-DOF actuator on top of LCD of a digitizer pen-tablet. The overview of the prototype system is shown in Fig. 12. We utilized a digitizer (Cintiq 22HD, Wacom Co., Ltd), which has a LCD display of 1920×1080 pixels and position detecting function using electromagnetic induction, which is compatible with the electrostatic actuator.

Two sets of the three-DOF actuators were placed on the display. A polyethylene sheet with a position and orientation sensor was placed on the display as an actuated object. The position and orientation sensor was extracted from an input pen of the digitizer. The circuit was cut and placed in a plastic container, as shown in Fig. 13. The size was 39×16×18 mm and the weight was 4.6 g. The XY resolution of the digitizer was set as 19200×10800 for the whole area and angle resolution of one degree. The total weight of the actuated

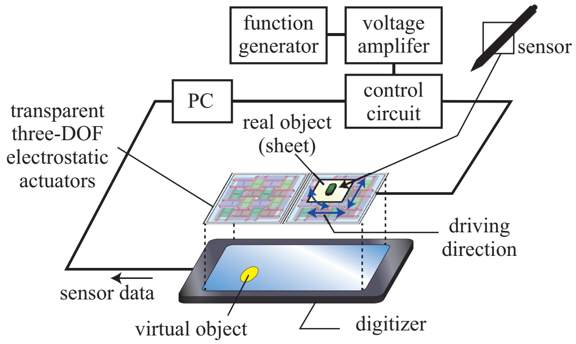


Figure 12: Overview of whole system using two 3-DOF electrodes placed on a digitizer.

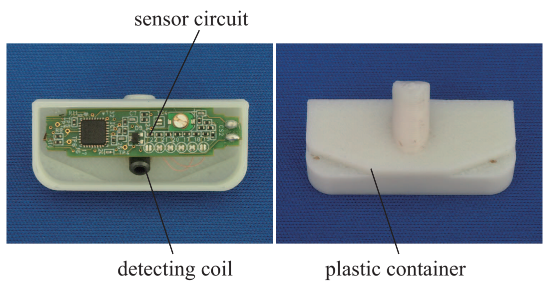


Figure 13: Position and orientation sensor fabricated using a circuit of an input pen of the digitizer.

object including the sensor shown in Fig. 14 was 5.8 g. Glass beads with 100 μm were scattered between a stator an a slider. A three-phase voltage with amplitude of 600 V_{0-p} and frequency of 100 Hz was used for actuation. Voltages were switched on and off by photo-mos relays, depending on the status of the application software and driving directions. Motions of the slider will be asynchronous under the voltage condition.

B. Position and orientation detecting

The position and orientation of the slider were detected using the digitizer, as shown in Fig. 15. The square in pink color is a temporary marker to indicate the detected position and orientation. In a relatively slower motion, the position and orientation are successfully obtained, and the marker position and orientation match with the slider, as shown in Fig. 15 (a). In contrast, the digitizer output shows a delay in a faster motion such as more than 100 mm/s, as shown in Fig. 15 (b). Since the program ran at about 100 Hz and the digitizer signal was successfully obtained at each time loop, the delay is not attributed to the program; it would be probably due to internal delay of the digitizer.

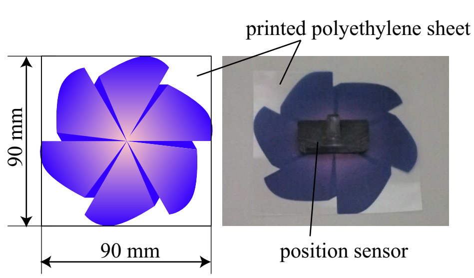
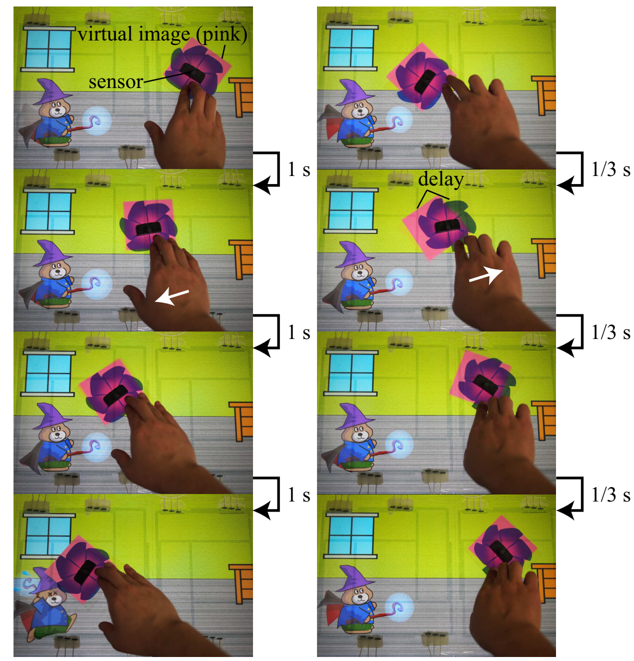


Figure 14: Slider of a polyethylene sheet with a fabricated position sensor.



(a) slower motion (b) faster motion

Figure 15: Detection of position and orientation on the interaction system. (a) In slower motion (b) In faster motion.

C. Demonstration

We programmed a simple application using the system, as shown in Fig. 16. A movie of the application can be found on the Internet [11]. In this application, a virtual character representing a wizard is walking around on the screen. Users can interact with the wizard through the actuated sheet. When a user throws the sheet to hit the character, it shows a puzzled behavior and steps back. At the same time, the sheet bounces back on the character. This motion was achieved by applying appropriate voltages to each electrode set based on the position and orientation of the slider. Asynchronous feature showed smooth motions without step-out vibration in cases of changing direction where higher driving forces were required. As another feature, the wizard character can throw a magic ball to the slider. The ball chases the slider and when they contact, the slider starts to rotate, as shown in Fig. 17. The asynchronous driving realized smooth and continuous rotation without any step-out. These results successfully demonstrated availability of a newly designed three-DOF transparent electrostatic actuator for a three-DOF user interaction.

VII. Conclusion and Future Work

This paper introduced a three-DOF transparent electrostatic actuator for active tangible user interaction. Asynchronous driving characteristics of the actuator achieved smooth X, Y, and diagonal translations and rotations of a plastic sheet. The smooth motions are suitable for a dynamic application. Combination of a digitizer and three-DOF actuators achieved three-DOF dynamic interaction between a user and a virtual character using a sheet-type real object. The simple demonstration program confirmed that the newly developed three-DOF transparent electrostatic actuator is suitable for a dynamic

Figure 16: Collision between a virtual character and a real object.

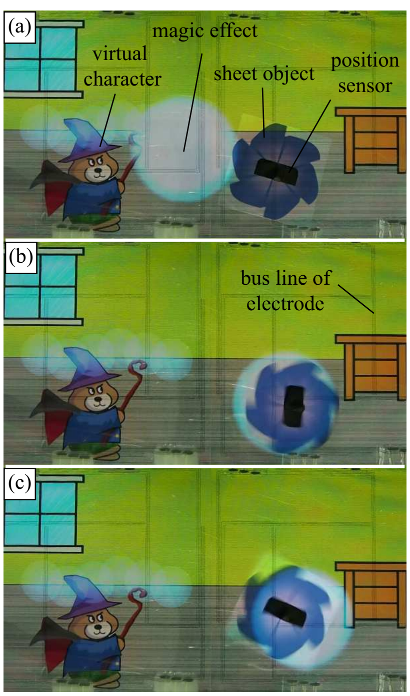


Figure 17: Rotating motion caused by a hit of virtual magic ball.

tangible user interaction. The usability of the proposed system would be evaluated in future work.

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