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Cross-Field Haptics: Multiple Direction Haptics Combined with Magnetic and Electrostatic Fields

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***Abstract*— We present a new method of rendering haptic textures that utilizes electrostatic and magnetic fields. In conventional research, a single physical quantity is used to render haptic textures. By contrast, our method combines multiple fields (electrostatic and magnetic). Although these fields have no direct interference, combining them provides benefits such as the ability to produce multi-resolution haptic images and synergistic effects on haptic perception. We investigate the increase in the variation of texture by comparing each single field method. Furthermore, we conduct user experiments and quantitative measurements.**

I. INTRODUCTION

Representing texture is a major issue during fabrication and manufacturing in many industries. Thus, approaches to fabricating everyday objects and digitally expressing their texture have become popular research topics. Although changing the texture of objects in the digital world is easy(i.e. simply by setting texture parameters), achieving it in the real world is difficult.

Recently, computer graphics have been employed in the real world for digital fabrication. For example, digital fabrication technologies have been used widely in laboratories and for consumer uses. Fabricated (e.g., 3D-milled, 3D-printed) objects represent their specific textures. Some methods exist for modifying textures after fabrication. For design and other industrial applications, having fabricated objects that are malleable (similar to computer graphics in the digital world) would be useful. In human computer-interaction and graphics communities, concepts such as programmable matter and radical atoms have been proposed.

Tactile feedback enables displaying texture and affordance. In conventional studies, interaction using tactile feedback has been actively researched. Most haptic feedback systems currently being studied are categorized as those that employ either wearable or non-wearable devices. Tactile feedback using wearable devices often employ force feedback devices (e.g., users wear the feedback devices on their arm [1] or fingertips [2]). Wearable devices can provide strong tactile feedback and tactile presentation in any condition. However, implementing larger wearable devices is difficult because mounting the device on the user is necessary. By contrast, tactile feedback that uses non-wearable devices mainly employs environmental-type tactile displays such as magnetic [3], electrostatic [4] and acoustic [5] fields. Force feedback devices [6] [7] have also been frequently employed in non-wearable devices and produce texture-like sensations through a handheld stylus. The user does not necessarily wear the device and the user's load becomes a low-level load.

In the present study, we aim to research new material interactions and to develop a new tactile device to express various textures. The proposed system physically deforms and changes the physical force between the finger and device. To achieve this, we combine magnetic and electrostatic fields. We use ferrofluid [8], which is a flexible liquid used in a magnetic field, and electrovibration [9] with adsorption force used in an electrostatic field to develop this device.

We compared the tactile sensations in a single and multiple field. Through verification, we determined that haptic feedback using multiple fields provides a wide range of tactile sensations compared with that using a single field. By combining different types of force (e.g., pull and push), the proposed system can display various textures. To the best of our knowledge, this is early study that combines multi-field physical quantities to render haptic textures.

The electrostatic and magnetic fields do not influence each other. Specifically, from our experiment(see Fig. 7), we determined that the fields do not influence each other's tactile presentation.

The remainder of this paper is organized as follows. First, we review related studies and principles. Then, we describe both the equipment used for implementation and the results of the experiments on haptic textures. Finally, a conclusions is provided. The proposed technology will facilitate new relationships between people and programmable textures in the real world.

II. RELATED WORK

Many related studies on haptic texture representation have been conducted. One approach is to use wearable devices to provide additional vibration to the user fingers [10]. Another approach is to employ haptic displays, which provide haptic feedback about smooth surfaces. The technologies employed in the latter approach include ultrasonic vibrations, electrostatic forces, and magnetic forces. These technologies have been applied to trackpads [11], pointing devices [12], and augmented reality (AR) systems [13].

A. Magnetic Field

Tactile presentation of magnetic fields include both direct and indirect presentation. For direct tactile feedback, placing a magnet on the finger [2] is possible. Zhang et al [14] rendered a 3D model in mid-air using an electromagnet array.

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In a direct tactile presentation, powerful tactile feedback is possible without touching the screen.

Indirect tactile feedback expresses the deformation of a surface. ForceForm [15] [16] achieves dynamic interaction by placing a surface with an attached magnet on an electromagnet array. In addition to providing haptics, BubbleWrap [17] allows for user interaction in witch hardness is detection by wrapping an electromagnet array and magnets in a cloth.

Ferrofluid is another mainstream method for tactile presentation that employs a magnetic field. Ferrofluid changes its viscosity based on the given magnetic field. Expressing an softness of an object by altering the viscosity of the ferrofluid is thus possible. Inaddition, expressing the bumpiness of a surface through fluid deformation is also possible. Linetic[18], which uses ferrofluid, combines hall effect sensing and actuation through electromagnetically manipulated ferrofluid. Magneto-rheological fluid [19] have similar properties to ferrofluid. When no magnetic field is provided, magneto-rheological fluid acts as a newtonian fluid such as water. When a magnetic field is provided, magneto-rheological fluid acts as non-newtonian fluid (Bingham fluids) such as butter. MudPad[3], which use magneto-rheological fluid, has a very low reaction time and can provide instant multi-point feedback for multitouch inputs. In this study, we used ferrofluid.

B. Electrostatic Field

We present haptic feedback using a technique called electrovibration [9]. In 1954, Mallinckrodt et al discovered the effects of electrovibration. Electrovibration creates a rubbery feeling when a person drags a dry finger over a conductive surface covered with a thin insulating layer that is excited with a high voltage signal. Force is generated in the direction in witch a movement is resisted by electrovibration. Therefore, the user can feel the pull force.

TeslaTouch [4] uses electrovibration, which adds a signal to an electrode. Interaction and touch displays were developed using electrode without a power unit. REVEL [13] employs TeslaTouch for AR. However, unlike TeslaTouch, REVEL uses reverse electrovibration that adds a signal to a user's finger. TeslaTouch is also used as a display for the visually impaired and for AR display [20] [21].

Electrovibration can provide haptic feedback without using a complicated actuator and device. However, moving a finger is unnecessary because the tactile presentation is related to the force generated between a moving finger and the surface. Therefore, providing one point haptic feedback such as a button is impossible.

C. Acoustic Field

Ultrasonic technology utilizes a squeeze film effect to reduce the friction of a flat surface and reproduces the texture by modulating ultrasonic vibrations. Diminished Haptics [22] renders real-world textures using a squeeze film and enables expressing various textures.

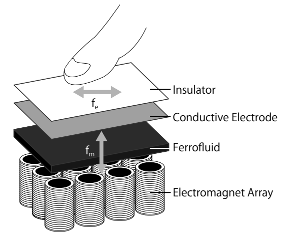

Fig. 1. System laysers. Note that fe is frictional force generated electrovibration and fm is push-up and push-down force generated by ferrofluid

Providing tactile sensations in mid-air is possible without encumbering the user with an actuator when using ultrasound [23] [24]. The position of the focal point can be changed because it is a representation of tactile behavior. MidAir [5] reflects a virtual image in the air and provides tactile feedback using an ultrasonic speaker based on the virtual image and finger location.

In [25], virtual objects were represented by air jets from an array of nozzles. In [26], air vortices were used to provide impact in midair. These can be explained as aerodynamic methods.

D. Cross-Field Haptics

This study combines multiple haptic technologies because they help overcome each other's disadvantages and improve interaction width.

wUbi-Pen [27] is a pencil-type tactile interface. wUbi-Pen consists of a vibrator, linear vibrator, speaker and pin array. In addition, it provides functions such as feedback drag, drop, and moving. Minamizawa et al [1] developed a tactile presentation that combines one-point kinesthetic and multipoint tactile feedback. They improved the accuracy of the feedback by combining haptic technologies. Impacto [28] was designed to render the haptic sensation of hitting and being hit in virtual reality. The researchers in [28] combined tactile stimulation with electrical muscle stimulation. Cross-Field Aerial Haptics [29] draw a tactile interface in the air by combining ultrasonic waves and laser plasmas. Hashizume et al [30] developed touch-type haptic device that combined magnetic and electrostatic field. The researchers in [30] described an implementation method. We experiment in addition to the explanation about an implementation method.

Cross-field haptics is not a widely studied field. However, we decided to use the electrostatic and magnetic fields simultaneously. Using both fields helps remove their drawbacks and is intended to offer wider tactile presentation. The magnetic field generates deformations that push up and down using ferrofluid. The electrostatic field generates force in horizontal directions using electrovibration. Upward, downward, rightward, and leftward directions can be achieved by combining adsorption force generated by electrostatic adsorption and the deformations generated by ferrofluid.

III. IMPLEMENTATION

A. Proposed System

Our device consists of an electromagnet array layer, a ferrofluid layer, and a conductive electrode layer (Fig. 1).

1) Electromagnet array layer: Ferrofluid was controlled using an electromagnet. The outer diameter of the electromagnet was 34 mm. The electromagnet possessed a holding force of 18.36 kgf. Furthermore, to ensure that a groove of the magnetic field was not created on the screen, 12 coils (three vertical and four horizontal) were laid on the 12 $\times$17 cm screen.

2) Ferrofluid layer: Ferrofluid, which appears as a black fluid, is a liquid whose viscosity changes in response to a magnetic field. Ferrofluids are prepared by dissolving nanoscale ferromagnetic particles in a solvent such as water or oil and remain strongly magnetic even in a fluid condition. That ferrofluids form spikes along magnetic field lines when the magnetic surface force exceeds the stabilizing effects of the fluid weight and surface tension is well known. If a magnetic field is provided the viscosity is linearly controllable using a magnetic field. In this study, we focused on the upward force of ferrofluid. When viscosity changes, the force pushing up a finger by vibration is generated by switching the magnetic field in the electromagnet.

3) Conductive electrode layer: Electrovibration [4] uses a conductive electrode. Electrovibration provides haptic feedback using electrostatic adhesion. Furthermore, it provides high-voltage electric vibration to the electrode. When a body is connected to ground and a finger moves on the electrode, force is generated. Force is generated in the direction in witch a movement is resisted. Therefore, a frictional force is generated.

Electrovibration is employed in two ways: adding a signal to a pole (electrovibration) and adding a signal to a body (reverse electrovibration). We chose electrovibration in this study. Often, the electricity generated between a metal plate and an aluminum seat penetrates to a conductive pole. Then, an electric current passes on to a body. Therefore covering a pole with an insulation layer is necessary. The insulating layer should be as thin as possible (on the order of several micrometers). In this study, a transparent conductive film on the electrode, which is an insulation coating agent (Hayacoat), was applied as the insulating layer. When this transparent electrode sheet is mounted on a touch or liquid crystal panel, if offers a clear advantage of bending easily. In addition, an insulation coating agent has the advantage of being easy to fabricate.

B. Control

Arduino DUE and a personal computer were used for controlling a circuit. A finger witch a marker attached is tracked with a camera, and the tracking position is used as input. A projector sends the image to a device based according to location of the tracked finger. An electronic signal is sent both to the electromagnet and to the electrode having a signal generator based on a tracked coordinate (Fig. 2).

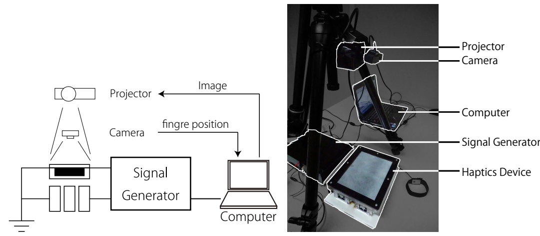

Fig. 2. System overview

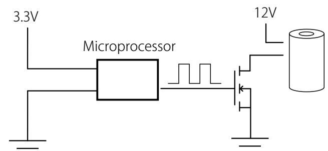

Fig. 3. Ferrofluid control circuit

A wave pulse of 12 V is input to the electromagnet that drives the ferrofluid (Fig. 3). The frequency of the wave pulse is controlled by a microprocessor. A signal corresponding to the location of the finger is input to the electromagnet. Not all of the electromagnets run simultaneously. An electromagnet of a necessary minimum is run and, therefore, allowing an excessive electric current to run is not necessary. Magnetic force conforms to the law of a reverse square and magnetic force become weak. Therefore, having the distance of the ferrofluid be as close as possible to an electromagnet is required.

Using a high-voltage electronic signal for electrovibration (Fig. 4) is necessary. electrovibration circuit combines a 555 timer and chopper circuit that boost pressure from 5 V to generate the voltage of 120 V. A chopper circuit is a circuit combined with FET, diode, coil, and condenser. A power supply of 120 V is switched by a pulse wave from a microprocessor using PhotoMOSRelay. The signal switched is sent to the pole. A wristband for static eliminations is placed on the user's body to ensure user's body is connected with ground.

We ensured that the system is safe for humans. The insulator was pitched by the electrode and the finger, and thus, an electric current did not flow into the human body. Even if it were to flow into the human body, it would be only a 0.5 mA electric current, as there are constant current diodes of 0.5 mA on the ground side that is connected to the human body.

C. Mutual Interference of the Field

In our device, electric and magnetic fields do not influence each other. We can consider separately and easily control each haptic feedback. The magnetic field generated from the electrostatic field depends only on the electric current that flows in an electrode. Electrovibration needs an electric current of only a few mA so generated magnetic field becomes exceedingly small. Because the operating ferrofluid needs a strong magnetic field, the magnetic field that occurs during electrovibration is ignored. In addition, an induced

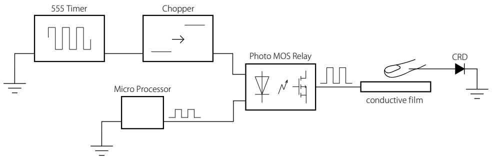

Fig. 4. Electrovibration control circuit

electromotive force results from the change in the magnetic field. Because the additional high voltage in electrovibration is more than 100V, voltage generated by the induced electromotive force can be ignored.

IV. EVALUATION

A. Subjective Evaluation

We conducted an evaluation of our system using six participants (Minimum age 20, Maximum 21 years old) to gauge their experience with tactile feedback. The frequency of the signal to the electromagnet and the electrode was changed. To deform the magnetic fluid, two signals of 20 and 100 Hz were added to the electromagnet, and each was presented to the subject. In order to generate electrovibration, three signals of 30, 100, and 300 Hz were added to the electrode and presented to the subject in the same manner. Furthermore, to present deformation and electrostatic attraction simultaneously, the afore-mentioned signals were simultaneously added. The participants were given three basic tasks. First, participants were told to describe the tactile sensations they experienced. Second, participants were told to select from the list the material the most closely matched the tactile sensation they experienced. Third, participants were asked level the tactile sensations for each of the five categories. Participants touched the screen up to 5 minutes, and then answered the questionnaire.

1) Results: Results are shown in Fig. 5. When no signal was added to the ferrofluid and electrovibration, the participants experienced only the soft elasticity of the ferrofluid. Regarding their interaction with ferrofluid only, the participants stated that it felt like a vibration or a heartbeat, although a change in texture was not felt. Regarding their interaction with electrovibration only, subjects felt friction and resistance, and participants stated that the texture approximated denim and sandpaper. When both ferrofluid and electrovibration were applied, the participants experienced both friction and vibration. When the frequency of electrovibration was low, most participants felt the material to be like rubber. However, when the frequency was high, the material felt like sandpaper. When we combined the magnetic and the electric field, we found that the viscosity, fineness and bulkiness seemed diminish as compared to when using a single field.

B. Quantitative evaluation

We focused on mutual interference of two fields of the finger vibration when a finger was traced on the surface. We measured the finger vibration in the case of: no haptic interaction, interaction only with a magnetic field , interaction only with an electrostatic field, and interaction with combined magnetic and electrostatic fields. Furthermore, to confirm that the electrostatic and magnetic fields did not affect each other, we measured the interaction during electrovibration when a magnetic field is present and interaction of ferrofluid when an electrostatic field is present. A haptic device for evaluation was composed of two electromagnets and 45 $\times$ 85mm conductive electrode. Acceleration of x, y, and z axes were measured using a three-axis accelerometer(M3AXIS-ADXL345) attached to the participant's fingernail (Fig. 6). Participants move the index finger to trace the screen at 80 mm / s. Signals of 50 and 100 were added to a conductive

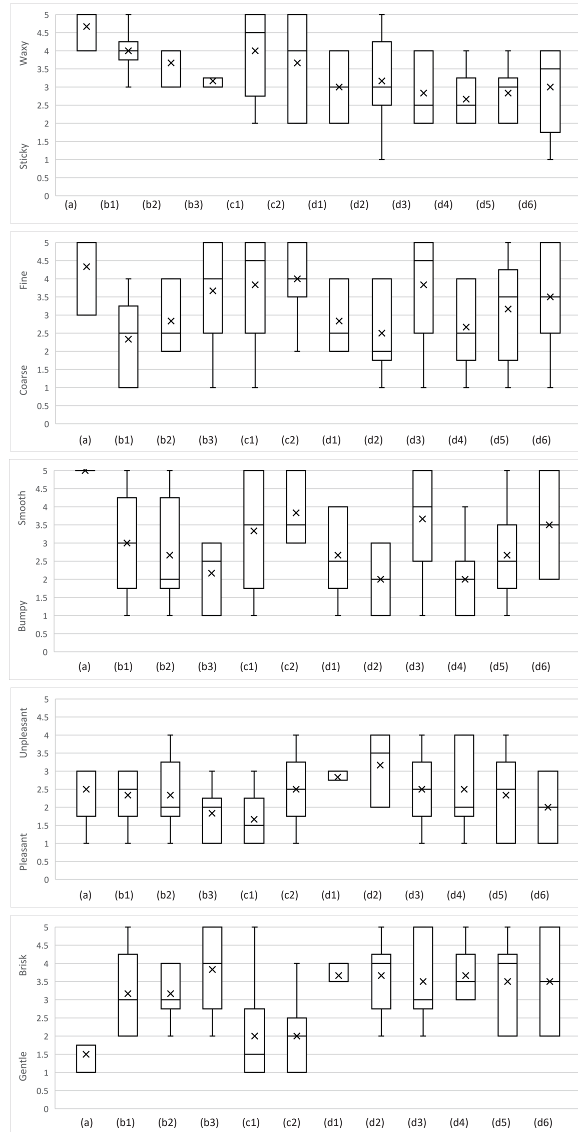

Fig. 5. Ratings of stickiness, fineness, smoothness, pleasantness and degrees of friction and vibration. (a) no haptic presentation, (b1)30Hz electrovibration, (b2)100Hz electrovibration, (b3)300Hz electrovibration, (c1)20Hz ferrofluid interaction, (c2)100Hz ferrofluid interaction, (d1)30Hz electrovibration and 20Hz ferrofluid interaction, (d2)100Hz electrovibration and 20Hz ferrofluid interaction, (d3)100Hz electrovibration and 20Hz ferrofluid interaction, (d4)30Hz electrovibration and 100Hz ferrofluid interaction, (d5)100Hz electrovibration and 100Hz ferrofluid interaction, (d6)100Hz electrovibration and 100Hz ferrofluid interaction

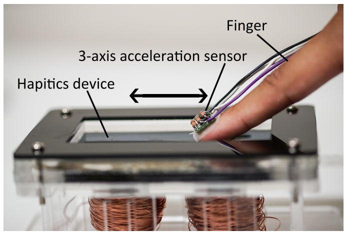

Fig. 6. Experimental overview: three-axis accelerometer attached to the fingernail with finger trace on the surface.

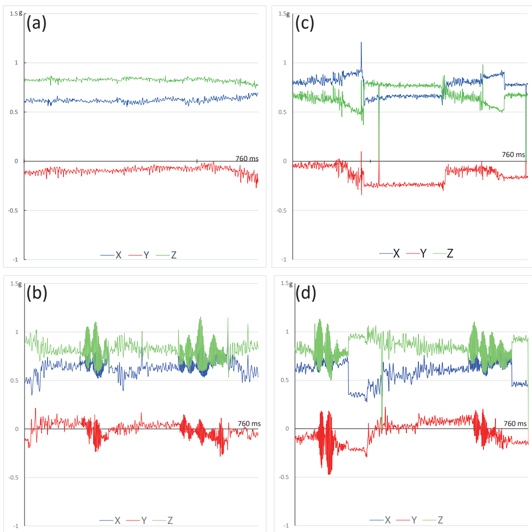

Fig. 7. Results for case of: (a)no haptic interaction, (b)interaction only with a magnetic field, (c)interaction only with an electrostatic field, (d)Interaction with combined magnetic and electrostatic fields.

electrode and electromagnets respectively.

1) Results: Results are shown Fig. 7 for vibrations of a finger in cases of no haptic interaction, interaction only with a magnetic field, interaction only with electrostatic field, and interaction with combined magnetic and electrostatic fields. Fig. 7 shows that the vibration waveforms of the finger are all different. When no haptic interaction occurs (Fig. 7 (a)), the finger does not vibrate greatly. This is because the screen is smooth. In the case of interaction only with a magnetic field (Fig. 7 (b)), the waveforms of all the axes oscillate. Deformation of the screen appears as the finger vibration. In the case of interaction only with an electrostatic field (Fig. 7 (c)), the finger vibrates like a catching on the surface. This is because an adsorption force is generated between the finger and surface as a result of electrovibration. In the case of interaction between the magnetic and electrostatic fields (Fig. 7 (d)), both the deformation of the screen and the adsorption power are characterized. By magnetic and electrostatic fields are applied simultaneously, either one of the generated forces does not decrease. The result shows without the two fields interfering with each other.

V. APPLICATIONS

In this study, we propose an application that combined magnetic and electric fields. Because we can independently manipulate these two fields, related research applications can also be implemented.

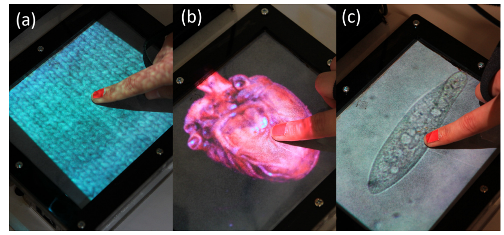

Fig. 8. (a) wool texture rendering, (b) reproduction of heart motion, (c) reproduction of paramecium caudatum.

A. Texture Rendering

An application that expresses various textures is possible (Fig. 8(a)). To realize this, we changed the frequency of the signal which add to electrode and frequency of the signal which add to electromagnet. The study in [4] expressed texture using friction; our application expresses texture using the force of ferrofluid in addition to friction.

B. Drag & Drop

Assisting GUI operation is possible by using the Push-Pull haptics such as drag & drop, which is a basic GUI operation. Using electrovibration our application produced friction when dragging files, icons and other similar items. A tactile illusion is created that is similar to that experienced in the real world. When objects arrive at a destination, we change the degree of stickiness of the ferrofluid. The user can determine whether the object has arrived at its destination by the hardness of the surface. This can be a useful guide for operation, and the moving speed the to the destination increases.

C. Body Tissue Simulation

Cross-field haptics can mimic the body tissue such as the heart and liver (Fig. 8(b)). In surgical operations, accurate operation to match the state of the body tissue is essential. The behavior can be matched easily if the specific organ can be expressed. To reproduce organs in virtual space, the texture of the organ surface, viscosity such as softness, and deformations such as pulsation must be expressed. Surface texture can be expressed using electrovibration, and viscosity and deformation can be expressed using the ferrofluid.

VI. DISCUSSION AND CONCLUSION

In this study, we developed a method that combines multiple haptics technologies. We showed that this method generates multiple direction forces (e.g., up and down, pull) using ferrofluid and electrovibration. We discussed width of the sense of touch presentation spread from an experiment of cross-field haptics. The device can be manufactured at a relatively low cost thus enabling it to be extended to other uses and applications. However, some problems remain. Because of the vibration force generated by ferrofluid is strong, the experience of friction with electrovibration became weak. Regulating the amount of electricity added to an electromagnet is necessary. During implementation of out method, some difficulties were encountered when using an insulation film on the electrode and during handling of the ferrofluid. Devising a simpler method for implementation is necessary for a future study.

Using our method, we can generate multidirectional forces (vertical direction, pulling force) using ferrofluid and electrovibration. We discussed changes experienced by users based on cross-field experiments. Our quantitative evaluation revealed that the tactile presentations do not interfere with each other. Experiments involving participants revealed that tactile sensations changing.

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