Development of user interface system using magnetic force by digital fabrication technology

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Contents

1 Introduction **1**
- 1.1 shape changing interface 1
- 1.2 Digital Fabrication Method 2
- 1.3 Magnetic Force 2

2 Related Work **4**
- 2.1 Actuation 4
- 2.2 Shape changing interface 4
- 2.3 Haptic 5
- 2.4 Levitation method 6
- 2.5 Digital Fabrication Method 6
- 2.6 Our Approach 7

3 Implementation **9**
- 3.1 Magnetic Actuator 9
  - 3.1.1 Electromgnet array 9
  - 3.1.2 Surface layer 11
  - 3.1.3 System configuration 11
- 3.2 Design System for Floating Object 13
  - 3.2.1 Magnetic Levitation 13
  - 3.2.2 Design Method for Levitated Object 13

4 Experiment **20**
- 4.1 Performance Evaluation 20
- 4.2 User study 20
  - 4.2.1 Operation to change material 20
  - 4.2.2 Feel of Pushing Surface 20
  - 4.2.3 Haptic feedback for palm 21

5 Design and Application **22**
- 5.1 Magnetic Actuator 22
  - 5.1.1 Button 22
  - 5.1.2 Table Top Actuator 23
  - 5.1.3 Wall Embed Application 23
  - 5.1.4 Design Consideration 24
  - 5.1.5 Haptic device 24

5.1.6 VR and AR experience . . . 24
5.2 Magnetic Levitation System . . . 25
5.2.1 Floating Display . . . 25

6 Discussion **26**
6.1 Magnetic Actuator . . . 26
6.1.1 Range of Motion . . . 26
6.1.2 Balance of Actuator's Body . . . 27
6.1.3 Shape of Slit . . . 27
6.1.4 Resolution of Haptic Feedback . . . 27
6.2 Magnetic Levitation System . . . 29
6.2.1 Shape Restriction . . . 29
6.2.2 Calculation Time . . . 29

7 Result and future work **31**

References **34**

List of Figures

1.1 Classification of commercial 3D printers 3

3.1 The electromagnets that using our actuator. The left one is the small electromagnet. The right one is the large electromagnet. Both of them are made from 2,000 turns of wire and the resistance value is 30-32 Ω. These electromagnets are made by GOKOH Co.,Ltd. 10
3.2 The design drawing of the enclosure. 10
3.3 Laser processing by CO2 laser processing machine. The CO2 laser processing is recently spread as the low cost fabrication method. 11
3.4 A: The surface materials for 3×3 cells. The structure of actuator is only one because it is mainly used for the button type application. It is processed for realize the large stroke. B: The surface materials for 4×4 cells that using smaller electromagnets. C: The surface materials for 4×4 cells that using lager electromagnets. 12
3.5 A: The surface of Morpho Sculptures wooden material version after processing. Even after applying triple helical structure processing, texture of the material can be expressed. B: The surface of Morpho Sculptures leather material version after processing. It's curled up and stand out the slit. Some material cause this phenomenon. It need to more adjust the laser setting to slenderer the laser. 12
3.6 A: Our actuator is constructed by the two layers. The first layer is the electromagnets layer. The second layer is the surface of actuator. It is made of a soft and thin plate materials such as wooden plate, leather, polypropylene, or cardboard. B: The coil array is driven by the micro computer. (1) We use Arduino UNO and Adafruit 16-channel PWM/Servo Shield to operate the coil array. (2) The signal from Arduino is amplified voltage by a circuit board. (3) 16 coils are attached one circuit board and one Servo Shield. . . . 12
3.7 Left: Magnetic levitation device. It consists of a magnetic levitation base and a levitation magnet. Right: Internal structure of magnetic levitation base. It contains circular permanent magnets, electromagnets and magnetic sensors. 14
3.8 Left: Example of operation screen of Rhinoceros. Right: Example of operation screen of Grasshopper. 15
3.9 Left: Base three-dimensional model of Stanford bunny used for verification. Right: Base three-dimensional model of banana used for verification. 15
3.10 Processing flow with Grasshopper 16

3.11 Result of 3D printing by applying our method to Stanford bunny. 17
3.12 Left: In case of the center of gravity is inside the bottom face of the target object. Right: In case of the center of gravity is outside the bottom face of the target object. 17
3.13 Processing flow with Grasshopper 18
3.14 Result of 3D printing by applying our method to banana. 19

4.1 A: The external form of our shape changing interface that consist of 3×3 actuators when turning off the switch. We set the marker for motion capture system. The motion capture view of the shape changing interface when turning on the switch. B: The result of the performance evaluation. The experimentation of the response speed and vibration. We turned on the actuator at the time point of 0 second. The response time takes 0.5 second and it has about 1 second vibration. Vibration is caused by the softness of the surface material. C-F: The switches that use for the experiment of touch feeling. C and D: tact switches for common electrical circuit. E: the emergency switch. F: the common analog switch. The switch F is the nearest feeling to our shape-changing interfaces. 21

5.1 Left: The first application example of our shape-changing interfaces. It could be a button such as a power switch or volume controller. We can change the material of its surface into the leather. Right: The application for AR/VR that using our shape-changing interfaces. It projects the picture of the switch onto the surface of the actuator. It is able to response to the user's action such as touch or jesture. 23
5.2 Left: The appearance of the table top actuator. It can control the movement of the small ball on it. Right: Our actuator can also use for the haptic device. It could present the haptic feedback for the palm. 24
5.3 Example using floating display for shop front display. 25

Chapter 1

Introduction

Various interfaces such as a display, a keyboard, a mouse, etc. are present in our familiar places. These interfaces simplify the interaction between computers and humans and help to blend computers into our lives. For example, humans have become able to receive computer output more visually and intuitively with the display. An interface such as a physically existing switch can be more intuitively appealed to a user by devising its shape depending on its function.

1.1 shape changing interface

Various shape changing interfaces have been proposed in previous studies. InFORM and ProjectFEELEX etc. are representative ones. These shape-changing interfaces realized various interactions like 2.5 dimensional display and actuation functions. However, since these shape changing interfaces use large actuators, they are costly to actually realize. Attempts to make own face change interface inexpensively have also been done, but it is troublesome and difficult to make easily. Conventional shape changing interface was driven by attaching a rod to the actuator array and moving it up and down. In this method it took time to process and assemble. Therefore, we propose a new shape change interface manufacturing method.

Many materials mass-produced in industrialized society in recent years are flat, thin and many squares. Within such a society, one-time machines like conventional shape-changing interfaces will take a long time and labor to popularize. We aimed to overcome the weak point of the conventional shape changing interface and make it easier for end users to manufacture and apply. In order to achieve this, it is necessary to devise the manufacturing method itself again. If it is possible to prepare a flat plate which is inexpensive and available and easy to process as a material, it becomes possible to disseminate shape-shaping interface at low cost. Recently processing machines such as laser cutters are beginning to spread generally, so it is becoming possible to suppress the cost of estuaries. Therefore, we redesigned the manufacturing method of face changing interface using flat plate which can realize low cost in both cost and labor in our method. Many objects in the world are made by processing flat plates, so processing of flat plates is an important factor. By using the manufacturing method of shape changing interface proposed by us, it becomes possible to naturally embed it in interior decoration such as furniture made from flat plate.

In this research, we propose a new shape - changing interface and fabricated prototype. Also, we evaluated the range of motion and deformation with prototype actually created. We examined the usefulness of the proposed method through experiments of subjects assuming that the end user uses it.

1.2 Digital Fabrication Method

3D printer can reproduce shapes by resin or metal based on three-dimensional model designed with CAD on computer. There are various types of 3D printers, such as fused deposition modeling (FDM), stereolithography, material jetting or powder sintering method. In the fused deposition modeling, we mainly use resins. To create three-dimensional objects extruding resin melted by heat through nozzles, stacking them in layers.Even in the stereolithography, it is a method of printing resin similarly to the fused deposition modeling.However, in the stereolithography method, a liquid ultraviolet curing resin is irradiated with an ultraviolet laser to solidify it in a layer shape to output a three-dimensional shape. Material jetting and powder sintering method are each a method of spraying powdered resin or metal and curing them by ultraviolet light or laser to create a three dimensional shape. Three-dimensional objects that output by printer are based on the model created on the computer. Since there are various features such as material hardness and time required for printing depending on the method and material of 3D printing, it is necessary to select output method and material according to purpose and required specification.

With the development of computer technology in recent years it has become common to make products that are optimized for purpose and personal capability. For example, Project Daniel is a project to make prosthetic hands tailored to the individual skeleton. In this project, the artificial hand outputted by the 3D printer is provided to the user. In this way, using a digital fabrication equipment such as a 3D printer, it has become possible for anyone to easily output a simulated model by a computer as having a form in the real world. It is no doubt that digital fabrication technology such as 3D printing will become a very important technology in the manufacturing method in future.

1.3 Magnetic Force

Magnetic force is a force acting on each other by a magnetic field such as a magnetic material such as a magnet or an object through which an electric current flows. There are many devices and systems using magnetic force in our surroundings as well. Recently, one example is a linear motor which runs with the car body levitating with magnetic force. Magnetic force has two kinds of polarities of S pole and N pole, and it has a characteristic that it attracts when the polarity is different and repels when the polarity is the same. The linear motor car described above is a system using the repulsive of the magnetic force. In our familiar places, there are also interfaces that use magnetic force. Many researches are realizing various interactions by the magnetic force generated by the electromagnet by embedding the electromagnet that generates the magnetic force in the table.

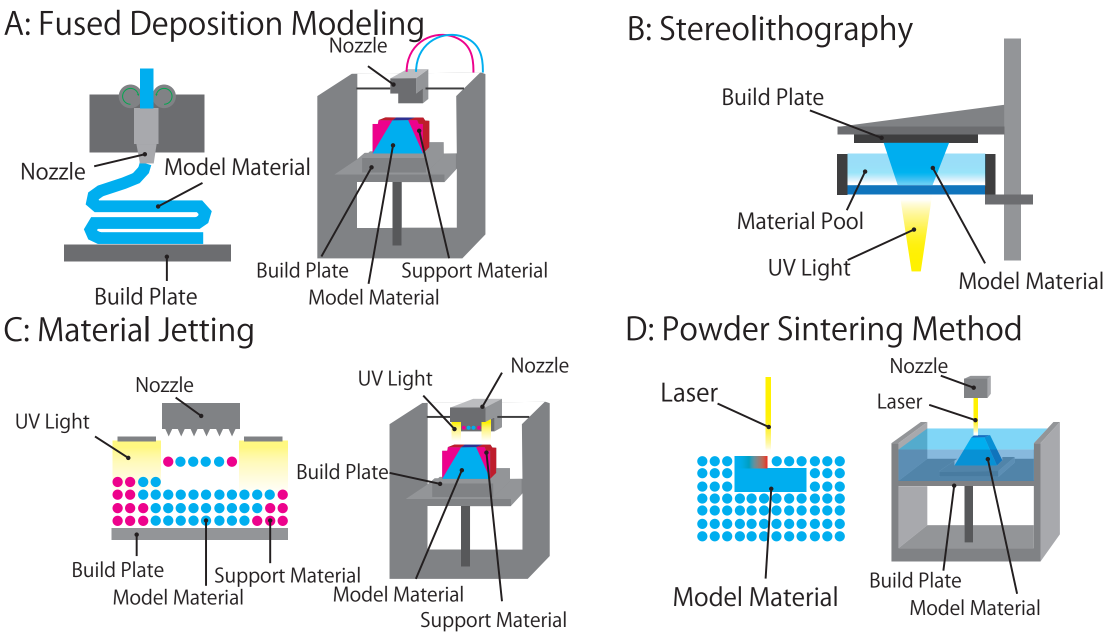

Figure 1.1: Classification of commercial 3D printers

Chapter 2

Related Work

2.1 Actuation

Various kinds of actuators have been investigated in HCI communities. The Actuated Workbench [1] by Pangaro *et al.* is the device that moves the object by magnetic force. In 2011, Lee *et al.* developed the MoleBot[2]. In this paper, the proposed device actuates 15,000 pins. Protrusions of this actuator take place under the pins that move vertically using neodymium magnets. The object placed on the pin is operated. In the same year, Wakita *et al.* developed the Programable Blobs [3] that drive slime mixed with iron powder by electromagnets. It is able to use the shape design tools. In the same year, another actuator that using electromagnets is developed by Kanai *et al.* . They developed buttons that called PocoPoco [4]. In PocoPoco, full-color LEDs are mounted on the actuator body, it enables users to have interaction. It is able to use musical application or othello game. ForceForm [5] by Tsimeris *et al.* in 2013 is the magnetic actuator that uses an array of electromagnets and a deformable membrane with permanent magnets attached to produce a interactive deformable surface. More recently, actuated curve interfaces called LineFORM [6] that use air pressure in 2015 was explored. LineFORM is also able to some interactions such as deform, touch or haptic detents. Coded Skelton [7] in 2016 use shape memory alloys in the actuator. It explored the fabrication method for user interfaces with mechanical metamaterial. In Madgets [8] by Weiss which advanced Finger Flux, it presents a system for the actuation of tangible magnetic widgets on interactive tabletop. FluxPaper [9] by Ogata *et al.* is the paper-based on physical movement and dynamic interaction system. It also used the magnetic force.

In this paper, we propose the new fabrication method to add the texture of the natural material for the electromagnet actuator. It is able to express the texture of everyday materials such as the wood or the leather.

2.2 Shape changing interface

Several studies propose shape-changing interfaces to extend Project FEELEX tried to provide users with a spatially continuous surface on which they can effectively touch an image using any part of their bare hand, including the palm. It was a pioneer study of 2.5-dimensional display which is added the three-dimensional feeling of the screen surface in addition to the two-dimensional display. InFORM also has aspects as a telepresence system with remote areas in addition to the functions as a conventional 2.5-dimensional display. Obake [10] by Gand *et al.* in 2013 use the silicone sheet as the surface of the display. The linear actuators under the silicone sheet move to transform. Direct and Gestural Interaction with Relief [11] by Leithinger *et al.* is the actuator array based on inFORM. It could recognize the gesture. These 2.5-dimentional displays have a strong affinity for interactions that display terrain undulations. In addition, GelTouch [12] by Miruchna *et al.* adds a layer of the Indium Tin Oxide gel of 2 mm to the display, thereby adding functions such as tactile feedback that can not be realized with ordinary displays. The gel-based layer that can selectively transition between soft and stiff to provide tactile multi-touch feedback. Lindlbauer *et al.* combined the shape-changing interfaces with the spacial augmented reality[13]. Haptic Chameleon [14] by Michelitsch refers to computer-controlled user interface devices that convey information to and from the user by altering their shape and feel. ShapeClip [15] by Hardy *et al.* is able to transform the normal LCD into the z-actuating shape-changing display. Emergeables [16] by Robinson *et al.* offer the flexibility of the graphic touch screen. Alexandra *et al.* report the shape changing structures that building on 3D printed cell structures [17].

These interfaces are made of plastics or iron. This characteristic does not effect normal usage. However, when using the interfaces embed natural texture such like wooden furniture, it will damage to these texture. Some researches proposed the interfaces that become familiar to our everyday life and materials. Martinez *et al.* presented the touchless interfaces in Mid-air [18]. We reported the new method to add the texture to interfaces. It realize the interface without damage to surrounding texture.

2.3 Haptic

There are various methods to express the haptic feedback. REVEL [19] using electrical stimulation extends the AR experience. It uses the electrovibration to express force- or tactile-feedback. Schorr *et al.* report the object manipulate method that using haptic feedback for fingertip [20]. The method of haptic feedback for fingertip is popular. WAVES [21] is a wearable haptic device for presenting three dimensions of translation and rotation guidance cues. In MudPad [22] by Jensen *et al.* in 2010 and Linetic [23] by Koh *et al.* in 2013 the magnetic fluid is used to express the tactile-feedback and they explore the interface haptically. Cross-Field Haptics [24] proposed a new haptic design method by using both electrical stimulation and tactile presentation by magnetic fluid. In Cross-Field Haptics, it is possible to express richer tactile sense by combining softness by magnetic fluid and rough feeling due to electrical stimulation. Magnetic Field Based Near Surface Haptic and Pointing Interface [25] by Karunanayaka *et al.* and Finger Flux [26] by Weiss *et al.* are examples of research that expresses tactile sense using the electromagnets and the permanent magnets. In these studies, a special tactile sense is imparted to the permanent magnets on the fingertip and the electromagnets on the object surface by magnetic force. Bubble Warp[27] by Bau *et al.* is the prototype of the haptic display that uses the magnetic force. Pinpad [28] by Jung *et al.* is the haptic feedback device that using small pins. This device can control other electric devices such like the laptop computer with haptic feedback.

2.4 Levitation method

Various methods for levitating objects are also been proposed. Recently, things like speakers and globe toys floating objects as interior are also on sale in general. With these commercially available products, by placing the magnetic levitation body on a specific stage, it is possible to maintain the balance between the repulsive force and the attractive force of the magnet to float the object. In Magnetic Field Control for Haptic Display by Qu *et al.* the objective is to simulate the generation of the magnetic field by the coil array as the tactile sense. [29] In a study that actually reproduces the tactile sense by the electromagnetic field by the coil array. [30] In this research, it is a display that represent tactile sense by controlling the magnetic field applied to MR fluid. In these studies, the target force is decided by simulating the electromagnetic field generated by the coil array beforehand. In the commercially available magnetic levitation device, it is possible to float the levitation body by controlling the output of the electromagnet based on the simulated target value in advance. It is basically impossible to move floating bodies and control the rotation of floating bodies. Therefore, in ZeroN by Lee *et al.* [31] , it is possible to move a magnetically levitated object in three dimensions by combining a magnetic levitation unit and an xy-plotter. In this method, multiple floating units are controlled by a plotter at the same time, thereby realizing control of plural floating bodies. However, it is impossible to realize a movement such that the floating bodies intersect each other on the moving route, or a movement in which the floating bodies pass by different heights. Some studies have realized control of the levitated body by placing a sensor outside. Berkelman *et al.* describes a method for evaluating the feasibility, efficiency, performance, etc. of a design obtained by calculation of the current, torque, etc. to the coil necessary for levitation of a cylindrical magnet on a coil array. [32] We compared the three kinds of magnetic levitation methods and verified their stability and feasibility. There is also a method to realize more stable levitation by attaching a marker such as a retroreflective material that enables optical tracking to the floating object on the coil array. In this study, an optical motion tracking system was applied to one levitation magnet to realize levitation control. [33] In this method, the ball joint achieves floating in a state where the movement of the magnet is partially fixed. In the method by berkelman in 2013 [34], a power source is mounted on the buoyant body and lighting the LED realizes control while identifying the current position of the levitating body I will. This method is a method that can control the translational movement of the buoyant body, roll, pitch, yaw rotation.

2.5 Digital Fabrication Method

As mentioned in the previous chapter, the progress of computer technology in recent years has to the appearance of digital fabrication technology in familiar places. The most characteristic one is 3D printer. 3D printer is a machine that forms a three-dimensional object by heating and melting a material such as resin or metal to a high temperature with heat or laser, and melting them and sticking them together. Originally 3D printers have been manufactured mainly by Stratasys and 3D Systems since they got the basic patent in the 1980's. [35] Recently, this patent has expired, so manufacturers other than those mentioned above also began manufacturing 3D printers. With this, the digital fabrication method by 3D printer appeared familiar to us. In the 3D printer modeling method, a method of slicing the original 3D model at the beginning and extruding the resin from the head of the printer one layer at a time on sliced layers to create a three-dimensional shape is common. The most popular 3D printing method to date is a method of melting and melting filaments made of resin or metal by FDM (Fused Deposition Modeling) method. [36] describes the relationship between the time required for rapid prototyping by FDM method and the accuracy of shaping. Rapid prototyping is one of the major applications of digital fabrication technology including 3D printers. Rapid prototyping refers to work that brushes up while making mock-ups with clay or wood while making products and works. In conventional rapid prototypes, there was a problem that cost was required for materials and processes for making prototypes. In the current digital fabrication technology, it is possible to make a 3D object designed by a computer into a three-dimensional object with a 3D printer, which makes it possible to create rapid prototypes more quickly and easily than before.This makes it possible to manufacture using 3D printers from prototyping and actual production of parts in various industries. In the field of human computer interaction, research combined with digital fabrication technology is increasing. Romain Prévost et al. Make it stand [37] proposed a system that adjusts the position of the center of gravity so that it can stand on a 3D model of various shapes with voxel carving or deformation in a specific posture doing. With this method, it was possible to produce a model that can stand with balance in whatever posture it looks like a 3D model displayed on CAD software of a computer. This aims to fill the gap between the world in computer CAD software and the real world. In Spin it [38] proposes a system that produces a frame that can rotate in an arbitrary posture under the same idea as make it stand. It is a technique to stably rotate an object that is asymmetric in appearance. In this way, with the recent digital fabrication technology, it is possible to control the characteristics inside the substance which was impossible in the days when the form was manually formed so far, and to control the characteristics of the substance It was easy to make it easier to have.

2.6 Our Approach

In this thesis, for the purpose of developing interface using magnetic force, we have constructed a system for designing models for actuators and magnetic levitation devices. In the actuator system, we prepared electromagnet arrays by arranging a plurality of electromagnets, succeeded in producing a thin, non-contact stroke by using the repulsive force of the electromagnet and the permanent magnet. The feature of this actuator is that we can use any material without loosing the texture of the surface. The texture of conventional actuators has been limited to those which are excellent workability such as plastics and metals. In this method, it be able to add to the surface material to the actuator function that without losing the texture of the surface material by digital fabrication technology.

In the model design system for the magnetic levitation device, I propose a center of gravity optimization method to levitate arbitrary models to the magnetic levitation device which is commercially available. By this method, we can be control and levitate at an arbitrary angle and posture for the arbitrary three-dimensional modelAs a result, it can be expected to improve the user experience in the user interface system using the magnetic levitation device, and to apply it to advertisements and the like.

Chapter 3

Implementation

In this thesis, we developed and verified user interface system using magnetic force. First, we developed and verified a shape changing interface using repulsive forces of electromagnets and permanent magnets. In this user interface system, a shape change actuator which does not lose the texture of the surface is realized a thin and compact actuator that use magnetic force.Next, we designed a levitating object design system in the magnetic levitation interface. In this system, we developed a shape optimization method for levitating arbitrary objects to the commercially available magnetic levitation interface.

3.1 Magnetic Actuator

The actuator developed in this thesis consists of two layers. The first layer is an actuator array composed of electromagnets. The second layer is a layer of material with a texture that will become the surface of the actuator.

3.1.1 Electromgnet array

For electromagnets layer, we use two patterns of electromagnets as the actuators (Figure 3.1). The larger one is height 37 mm, and 24 mm in diameter. The smaller one is height 19.7 mm, and 14 mm in diameter. The larger coil is made from 2,000 turns of wire. The rated voltage is 12V, and the resistance value is 30-32 Ω. The smaller coil is made from the same number of wires. The rated voltage is 24V, and the resistance value is 30-32 Ω. Both of electromagnets are shown in Figure 3.6A. We put the iron core in both electromagnets as the magnetic core. We use these electromagnets for producing the magnetic force.

We fabricated the enclosure of electromagnet array using the 3D printer and CO2 laser cutter (Figure 3.2). It could reduce the cost to mass production. The size of the enclosures are 66mm×66mm×37mm (W×D×H) for 3×3 large electromagnet array, 73mm×73mm×31.5mm for 4×4 small electromagnets array and 120mm×120mm×65mm for 4×4 large electromagnet array. The smaller enclosure is made by 3D printer with PLA, the lager one is made from the processed acrylic plate by CO2 laser and we assembled it for the box shape. We created three cells for prototypes: 3×3 cells, 4×4 cells using smaller electromagnets and 4×4 cells using larger electromagnets for our applications. All of these cells can combine multiple cells for each size of them. The outline of these prototypes is shown in Figure 3.6.

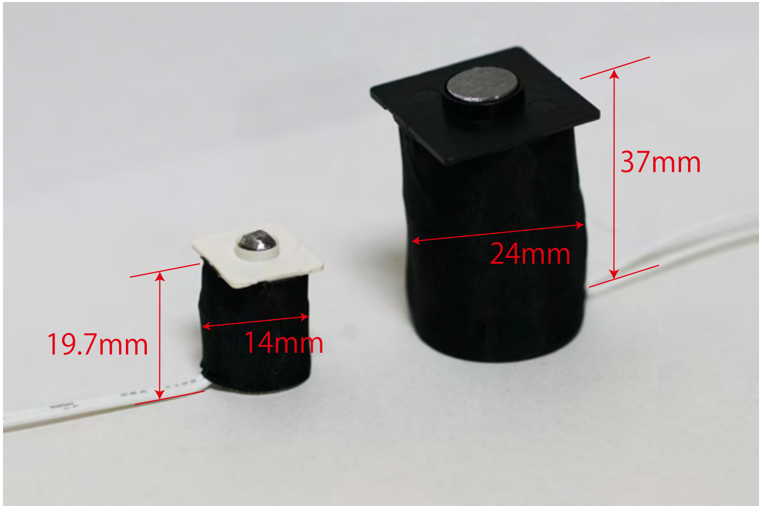

Figure 3.1: The electromagnets that using our actuator. The left one is the small electromagnet. The right one is the large electromagnet. Both of them are made from 2,000 turns of wire and the resistance value is 30-32 Ω. These electromagnets are made by GOKOH Co.,Ltd.

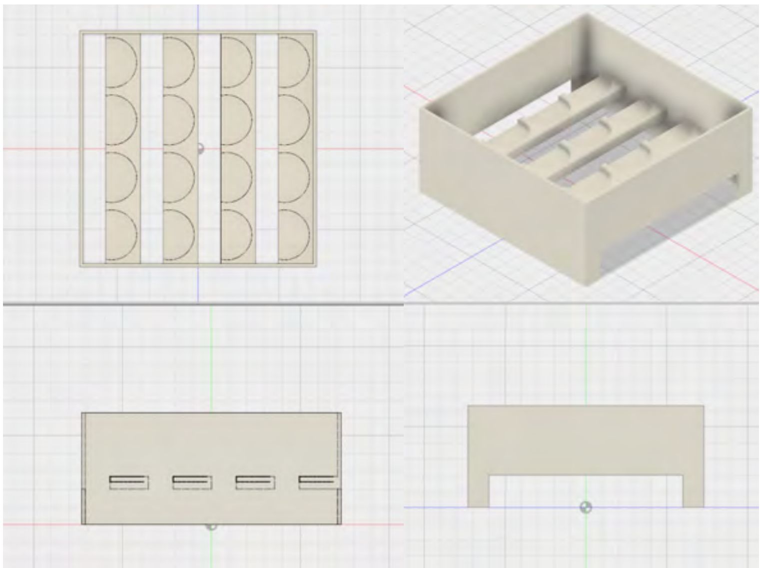

Figure 3.2: The design drawing of the enclosure.

3.1.2 Surface layer

The second layer is a layer to be the surface of the actuator. It is made of soft and thin board material like wooden board, leather, polypropylene, or cardboard. The machined shape of the surface is triple spiral turning and the turning width is designed to be about 5 mm. Processing for realizing a stroke as an actuator is performed without impairing the texture of the surface. In order to protect the surface texture of the surface, when the function as the actuator is OFF, the surface layer needs to be in a flat state. In addition, it is necessary to be able not to see the processed traces even in a flat state. Therefore, in this study, processing by CO2 laser was adopted. Processing with CO2 laser is inexpensive and thin sheet processing such as wooden sheet and synthetic leather sheet is possible (Figure 3.3). By adopting CO2 laser processing, it is possible to change the material of the surface layer not only to polypropylene board but also to acrylic board, soft wood board, cardboard (Figure 3.5) . The configuration of the actuator part is shown in Figure 3.4. By using these coil arrays and plate materials, it is possible to change the material of the surface of the shape changing user interface to an arbitrary one.

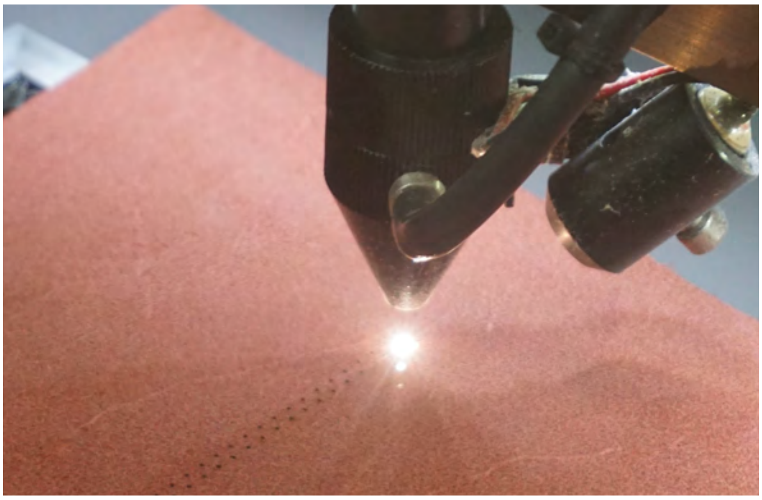

Figure 3.3: Laser processing by CO2 laser processing machine. The CO2 laser processing is recently spread as the low cost fabrication method.

3.1.3 System configuration

Our system configuration is shown in Figure 3.6. The coil array is driven by the micro computer. We use Arduino UNO[1] and Adafruit 16-channel PWM/Servo Shield[2] (Figure 3.6B(1)) to operate the coil array. The signal from Arduino is amplified voltage by a circuit board(Figure 3.6B(2)). 16 coils are attached to one circuit board and one Servo Shield (Figure 3.6B(3)). The reason that we use the electromagnets as actuator is the thickness of the system could be smaller than conventional actuators. When the actuator is driven by the magnetic force, the coil array and the surface plate does not contact with. Therefore, to exchange of the surface materials becomes easy. Our system is operated by Processing[3].

[1] https://store.arduino.cc/usa/arduino-uno-rev3
[2] https://www.adafruit.com/product/1411
[3] https://processing.org/

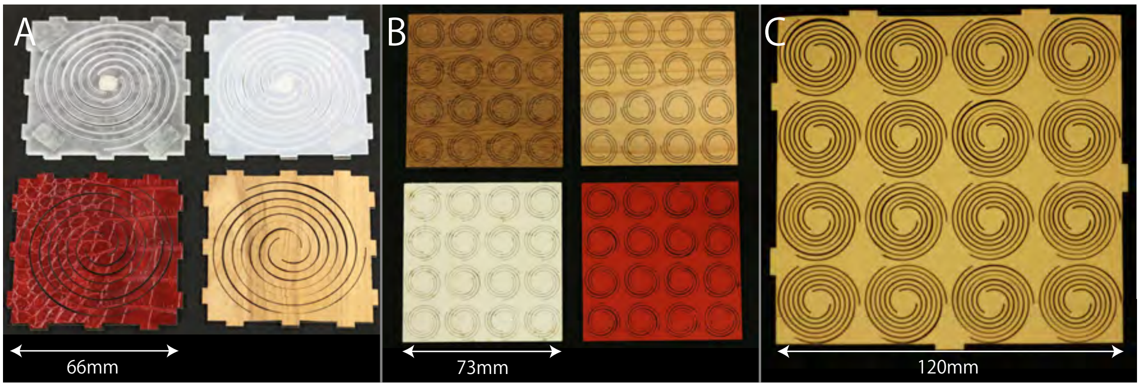

Figure 3.4: A: The surface materials for 3×3 cells. The structure of actuator is only one because it is mainly used for the button type application. It is processed for realize the large stroke. B: The surface materials for 4×4 cells that using smaller electromagnets. C: The surface materials for 4×4 cells that using lager electromagnets.

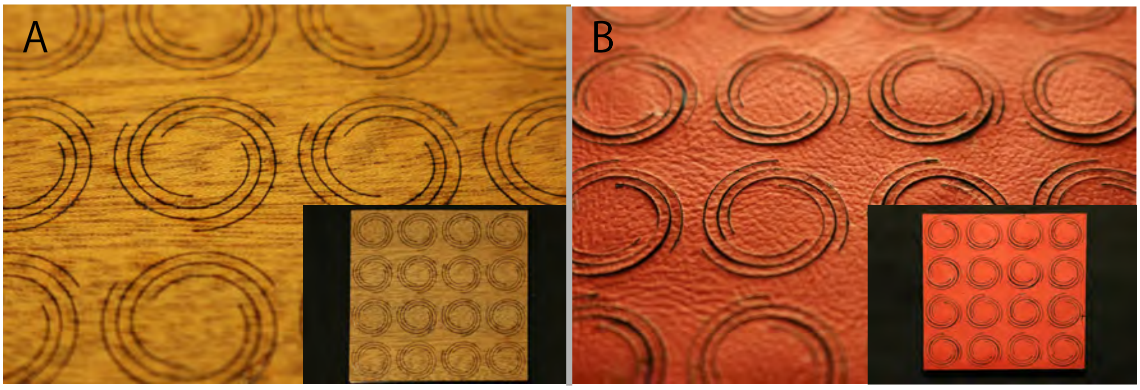

Figure 3.5: A: The surface of Morpho Sculptures wooden material version after processing. Even after applying triple helical structure processing, texture of the material can be expressed. B: The surface of Morpho Sculptures leather material version after processing. It's curled up and stand out the slit. Some material cause this phenomenon. It need to more adjust the laser setting to slenderer the laser.

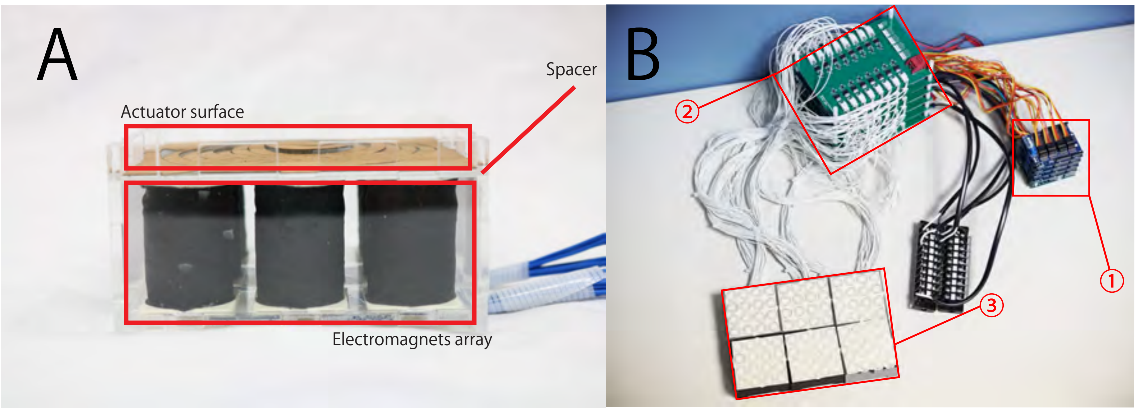

Figure 3.6: A: Our actuator is constructed by the two layers. The first layer is the electromagnets layer. The second layer is the surface of actuator. It is made of a soft and thin plate materials such as wooden plate, leather, polypropylene, or cardboard. B: The coil array is driven by the micro computer. (1) We use Arduino UNO and Adafruit 16-channel PWM/Servo Shield to operate the coil array. (2) The signal from Arduino is amplified voltage by a circuit board. (3) 16 coils are attached one circuit board and one Servo Shield.

3.2 Design System for Floating Object

In addition to the shape changing user interface with the electromagnet array described above, in this paper we also developed a system to optimize arbitrary models for levitating to magnetic levitation systems which are commercially available. The magnetic levitation system currently commercially available is designed to levitate the specific magnets against the specific stage. Commercially available levitating device can only float an object that center of gravity is not off center, its application has been limited so far. Therefore, in this thesis, we aim to widen the application of current magnetic levitation equipment by designing suspended matters of common magnetic levitation devices using digital fabrication technology.

3.2.1 Magnetic Levitation

This section describes magnetic levitation, which is an important point in this research.

Basic Theory of Magnetic Levitation

There is what is called a magnetic levitation spinning top. Magnetic levitating spinning top is the spinning top that floats above the permanent magnet of the base. In this magnetic levitated spinning top, a ring shaped permanent magnet creates a force to levitate the spinning top. It is levitating due to the repulsion of the ring magnet and the magnetic material. The vertical force in this configuration is balanced by the vertical force of the ring magnet and the gravity acting on the levitating object. The force affecting in the lateral direction of the levitating object balances the centrifugal force by placing the levitated object as a spinning top. However, in this configuration, even if the magnetic levitation base is slightly inclined or only slight force is exerted on the spinning top itself by the wind, it collapses from the stable state, and the levitated object falls. In order to absorb the forces affecting on the levitation side magnets and the deviation of the levitation side magnets in addition to the ring type magnet in the recent magnetic levitation device, stabilization by electromagnet is attempted.

Magnetic Levitation Device

The composition of the magnetic levitation system is shown in Figure 3.7. This magnetic levitation system mainly consists of a permanent magnet, a sensor, and a control circuit. The levitation side magnet is floated with this magnetic levitating device. The general principle of magnetic levitation is a method of generating a repulsive force by a strong permanent magnet, lifting an object and controlling the balance of the object with an electromagnet attached to the permanent magnet. The distance between the levitating side magnet and the magnetic levitation device is measured by the Hall sensor contained in the magnetic levitation device, and the control value of the electromagnet is determined.

3.2.2 Design Method for Levitated Object

In the conventional magnetic levitation apparatus, the object for levitation is mounted on the floating magnet attached to the floating device, and the floating object is restricted to the one in which the center of gravity coincides with the center of the floating magnet to

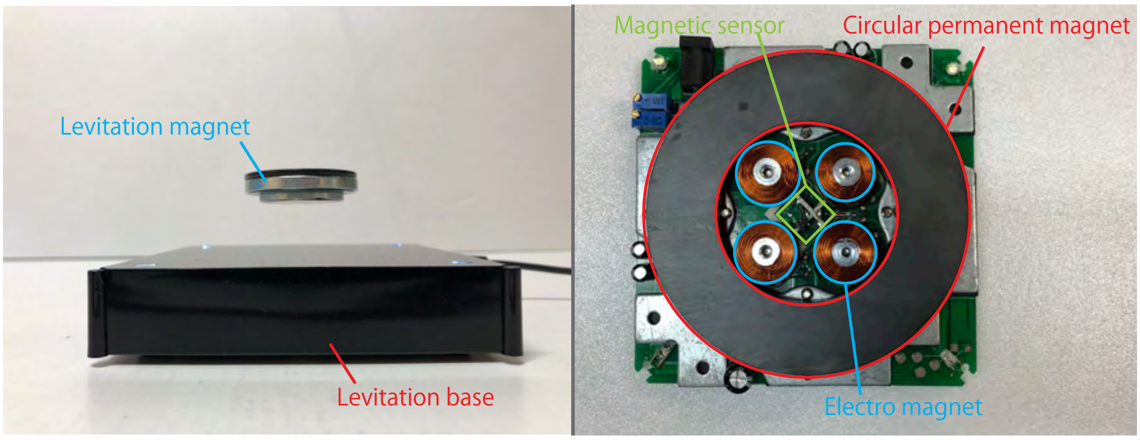

Figure 3.7: Left: Magnetic levitation device. It consists of a magnetic levitation base and a levitation magnet. Right: Internal structure of magnetic levitation base. It contains circular permanent magnets, electromagnets and magnetic sensors.

some extent. However, it is not that many objects that users want to levitate apply to this condition. For this reason, in the conventional magnetic levitation device, a spherical body like a globe or a disk like a UFO has been used as an example of application. Currently there are restrictions on shape and center of gravity position. The user interface experience using the magnetic levitation device is very limited. Therefore, in this research, we adjusted the position of the center of gravity of the levitated object in order to improve the user interface experience in the magnetic levitation device. It is able to levitate the object that the center of gravity is biased or the shape is not constant in the circumferential direction. We propose a digital fabrication method that can levitate arbitrary objects.

In this method, Rhinoceros which is a three-dimensional modeling tool was used for processing three-dimensional models. Rhinoceros has features such as creation, editing and analysis of 3D shapes, drawing creation and rendering. It is used not only in simple three-dimensional model production but also in a wide range of fields such as architectural design and FDM analysis. An example of the operation screen of rhinoceros is shown in Figure 3.8(Left). Various plugins are provided for Rhinoceros, and in this research we used the visual programming language called Grasshopper. Grasshopper can add various processing to the target three-dimensional model by combining elements that add certain operations to the model called component. An example of Grasshopper's operation screen is shown in Figure 3.8(Right). In this research, Rhinoceros and its plug-in Grasshopper were used mainly to process the internal structure of the three-dimensional model and to optimize the position of the center of gravity.

In order to make an arbitrary three-dimensional model levitable, it is necessary to align the center of gravity of the levitate model main body with the center position of the levitation side magnet. When trying to levitate an arbitrary model, the difficulty of levitation varies depending on which side of the model is set as the bottom or how to set the angle at the levitation. In this method, the processing is divided into two patterns according to the arrangement of the model, thereby reducing the amount of calculation, speeding up the processing, and enabling the model to be processed efficiently. The first

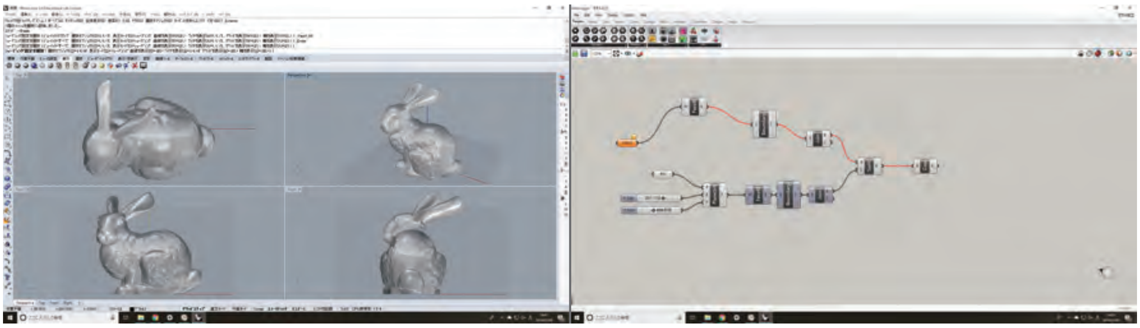

Figure 3.8: Left: Example of operation screen of Rhinoceros. Right: Example of operation screen of Grasshopper.

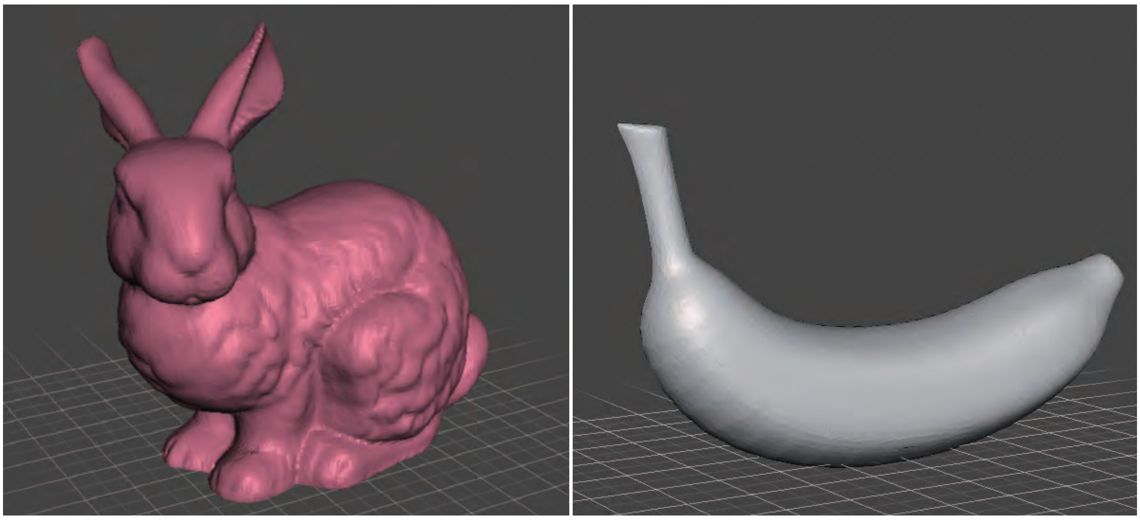

Figure 3.9: Left: Base three-dimensional model of Stanford bunny used for verification. Right: Base three-dimensional model of banana used for verification.

pattern of classification is the case where the center of gravity of the target model is originally on the bottom of the model as shown in Figure 3.9(Left). In this case, the process is very simple and only ensures a space for accommodating the levitating magnet at the position on the Z axis of the center of gravity position of the target model. Another pattern is the case there is a center of gravity of the target model outside the bottom of the levitating model (Figure 3.9(Right)). In this case you can not fill the floating magnets on the Z axis of the center of gravity position of the target model. Therefore, it is necessary to adjust the structure inside the model and place the center of gravity position within the bottom of the model.

In case of the target model's center of gravity is inside of the bottom face

The composition of Grasshopper when the center of gravity is inside the target model is shown in Figure 3.10. When the center of gravity is inside the bottom face of the target model, optimization to the target model was carried out in the following flow.

Import the three-dimensional model which is the outline of the levitated object.

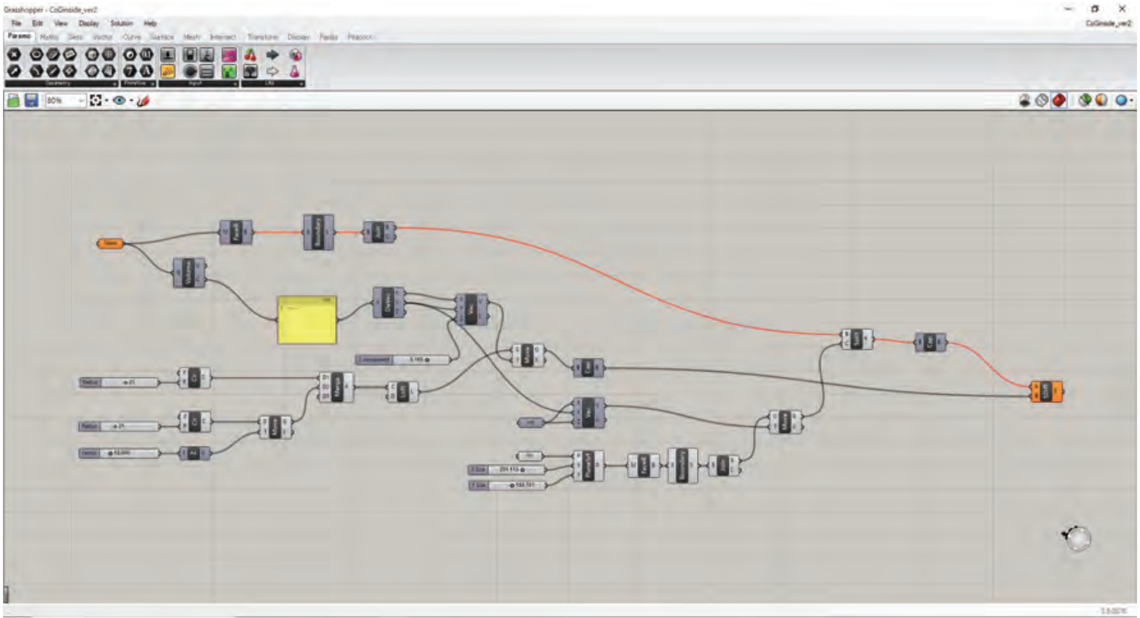

Figure 3.10: Processing flow with Grasshopper

First, import the target three-dimensional model on Rhinoceros and store it in the mesh component in Grasshopper. The stored target model is converted into Brep which is a solid form for easy processing in Grasshopper.

Create a model of the levitation magnet.

Three-dimensional modeling of the levitation magnets to create a space for storing the levitation magnets in the target model. The model of the levitated magnet is also converted to the Brep format like the target model.

Calculate the center of gravity position of the 3D model.

Next, the gravity center position of the input model is calculated using Grasshopper's *Volume* component. The position of the model of the levitation magnet is adjusted so that the Z axis of the calculated center of gravity position and the Z axis of the center of gravity of the floating magnet model coincide.

3D print the generated 3D model.

The model is divided into two so that the processed target model can be printed by 3D printing to make it actually can levitate. A 3D printed version of the generated 3D model is shown in Figure 3.11(Left). Levitate the model by placing a levitating magnet in the finished model. Figure 3.11(Right) shows how you actually floated it.

The target model with the center of gravity in the bottom plane can be levitated by the above flow.

In case of the target model's center of gravity is outside of the bottom face

If the center of gravity of the target model lies outside the bottom of the posture you want to levitate, it will be a different approach than the one described above. Figure 3.12 Right showed the situation where the center of gravity of the target model lies outside the

Figure 3.11: Result of 3D printing by applying our method to Stanford bunny.

bottom. In this case, it is impossible to arrange the floating magnets on the Z axis of the center of gravity position as it is. Even if a magnet is placed on the bottom surface, it falls when the model is levitated. Therefore, in order to make the magnetic levitation with the target attitude, it becomes necessary to add the hand to the internal structure of the model to control the position of the center of gravity. Since the center of gravity position is calculated many times in order to make the center of gravity position of the model coincide with the center of gravity position of the levitating magnet, the center of gravity position of the target model increases considerably both in calculation amount and time than in the inside of the bottom surface. The composition of Grasshopper when the center of gravity of the target model is outside the bottom is shown in Figure 3.13. This configuration uses a plugin to run Python code within Grasshopper. The processing flow inside the target model is as follows.

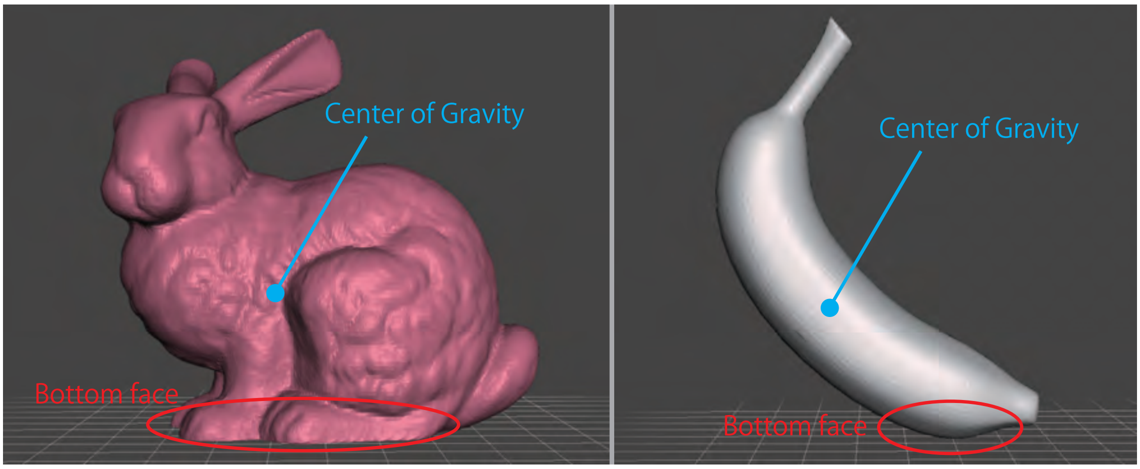

Figure 3.12: Left: In case of the center of gravity is inside the bottom face of the target object. Right: In case of the center of gravity is outside the bottom face of the target object.

Import the three-dimensional model which is the outline of the levitated object.

As in the previous section, import the target 3D model on Rhinoceros and store it in the mesh component in Grasshopper. The stored target model is converted into Brep

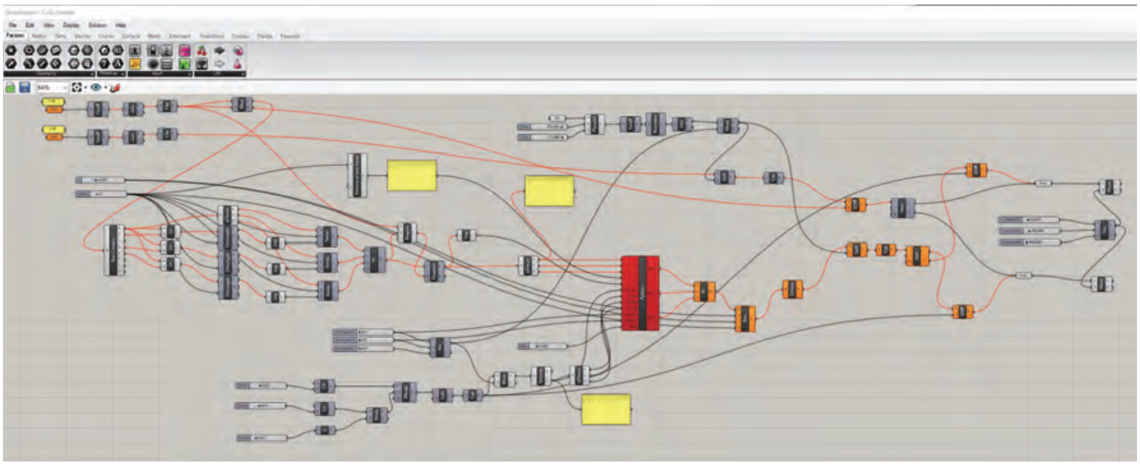

Figure 3.13: Processing flow with Grasshopper

which is a solid form for easy processing in Grasshopper.

Create a model of the levitation magnet.
Three-dimensional modeling of the levitation magnets to create a space for storing the levitation magnets in the target model. The model of the levitated magnet is also converted to the Brep format like the target model.

Voxelize the target model.
Although it is ideal in terms of accuracy to process a three-dimensional model as it is, in reality it takes too much computation time, so in this method, the target model is voxelized and the processing time is shortened. By converting the model to voxels, it is possible to digitally process the three-dimensional model. Calculation time is influenced by adjusting the size of the voxel. Although processing with fine voxels improves accuracy, calculation cost increases, so it is necessary to calculate with a large voxel to some extent.

Calculate the center of gravity of the voxelized 3D model.
Calculate the center of gravity position of the voxelized model with Python code in Grasshopper. This value is the initial value of the subsequent processing. At the same time, Grasshopper's *Volume* component calculates the position of the center of gravity of the levitated magnet and uses that coordinate as the input value of the Python code. A value with a certain error range in this value is taken as the target value.

Processing to remove voxels
Voxels are scraped so that the Z axis of the center of gravity of the voxelized model falls within the range of the target value. The center-of-gravity position of the voxelized model calculated in (4) is defined as the initial value, and the center-of-gravity position of the levitation magnet is set as the target value. When the center of gravity position of the voxel is different from the target value, an operation of deleting the voxel farthest from the target value coordinates is performed. Calculate the center of gravity position of the voxel after deleting the voxel. Also, the center of gravity position of the voxel is compared with the target

value, and if it is within a certain error range from the target value, the process is terminated. If the center of gravity position of the voxel is within a certain error range from the target value, it repeats until the center of gravity of the voxel falls within the range of the target value and outputs a list of successful voxels after success.

Process for making a levitated object

Based on the list of voxels output in (5), we generate a voxel model on Rhinoceros. In order to make the generated model an internal structure, voxels are placed inside the target model and a blue operation is performed. This completes the model in which the outer shape contains the voxels for optimizing the center of gravity in the form of the target model. A space for inserting the floating magnets here is created and the model itself is completed.

3D print the generated 3D model.

As in the case where the center of gravity is within the bottom plane, the model is divided into two so as to print the processed target model by 3D printing and make it actually levitable. A 3D printed version of the generated 3D model is shown in Figure 3.14(Left). Levitate the model by placing a levitating magnet in the finished model. Figure 3.14(Right) shows how it actually floats.

With the above flow, optimization of the center of gravity of the floating body is performed, and a model of an arbitrary shape is set as a levitable model.

Figure 3.14: Result of 3D printing by applying our method to banana.

Chapter 4

Experiment

Our method enables to use various materials for the surface of the actuator. In addition, it is possible to use Morpho Sculptures as the haptic device present tactile sensation to the palm of hand. In this section, we evaluate the characteristic of our actuator.

4.1 Performance Evaluation

We measured the response of the actuator. We use the polypropylene plate that thickness is 1mm and it is used for 12V. We set the marker for the motion capture system to measure the motion of the actuator. The motion capture system is able to measure 20fps and the accuracy is 0.01mm. As the result, the maximum displacement is 64mm and it stabled at 30mm. The response time is 0.5 second and it has vibration for 1second. This result shows our actuator have high responsiveness. The vibration dose not need to consider the performance of actuator. Figure 4.1 shows the result of performance evaluation.

4.2 User study

4.2.1 Operation to change material

We conducted the experiment to evaluate the difficulty to change the surface materials. For users, we asked some questions for participants of our shape-changing interfaces. In the experiment, test subjects are changing the surface of the actuator and evaluate it's difficulty for five-grade evaluation. We use 4 types of the surface material: wood, leather, PET resin, and polypropylene. As a result of the experiments, 4 out of 8 people(7 males and 1 female) answered that they feel changing surface is easy. It is considered because of the scratch of our structure. Therefore, we needs to be able to improve this problem.

4.2.2 Feel of Pushing Surface

We also evaluate the touch feeling of our shape-changing interfaces. We use 4 kinds of switches for this experiment. We prepare 8 kinds of participants(7 males and 1 female). The age of them between 19 to 22. The switches that used this experiment are shown in Figure 4.1C-F. The result of experiment, the switch of D is chosen by 7 out of 8 people. Therefore, we use this switch to a projection on the application.

4.2.3 Haptic feedback for palm

We evaluate the performance of our shape-changing interfaces as haptic device. The participants put there hand on the actuator surface and they feel the haptic feedback from the actuator array. We asked 42 participants about the feeling of it and evaluated using five stages Likert scale(do not feel - feel). The question is "Could you feel the haptic feedback from the actuator array?". As the result, 92.8% participants answered that they could feel the haptic feedback from the actuator array. Other participants answered intermediate answer. There is no participant answered they could not feel the haptic feedback.

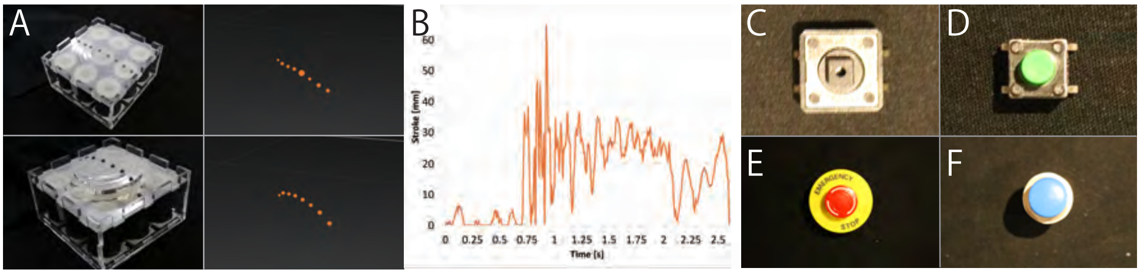

Figure 4.1: A: The external form of our shape changing interface that consist of 3×3 actuators when turning off the switch. We set the marker for motion capture system. The motion capture view of the shape changing interface when turning on the switch. B: The result of the performance evaluation. The experimentation of the response speed and vibration. We turned on the actuator at the time point of 0 second. The response time takes 0.5 second and it has about 1 second vibration. Vibration is caused by the softness of the surface material. C-F: The switches that use for the experiment of touch feeling. C and D: tact switches for common electrical circuit. E: the emergency switch. F: the common analog switch. The switch F is the nearest feeling to our shape-changing interfaces.

Chapter 5

Design and Application

So far we have discussed the shaping interface using the force of the magnet and the optimization method of the center of gravity of the floating body in the magnetic levitation device. In this section, application examples of these systems will be described.

5.1 Magnetic Actuator

First, consider the interaction design and application examples of the shape changing interface fabricated in this research. This shape changing interface is thinner than conventional ones, and has the feature that the material of the surface can be freely changed. Therefore, in the following application examples, in addition to those that change the texture of interfaces that exist daily in buttons and the like, an example of embedding a new interface at a place where it was difficult to embed the interface so far is shown. The shape change interface of this research can realize various applications ranging from a small number and a small scale to a large scale consisting of many. Shape changing actuators for applications have one cell consisting of 4 $\times$4 actuator arrays and others consisting of 3 $\times$3. For small-scale applications, use this cell alone. In the case of large-scale applications, it can be realized by using 2 to 4 cells. Below are some examples of applications.

5.1.1 Button

Examples of small applications include buttons such as power and volume. This is an application composed of one cell. Use the protrusion of the actuator as a button. You can embed a button like interface on the surface which is originally covered with material with texture like wood or leather like the surface of a car dashboard or table. It is difficult to recognize this actuator as a button because this actuator is flat when the switch is off. Since it can function as a button only when the switch is turned ON, it is possible to add a function as an interface without damaging surrounding texture. In addition, you can add functions by displaying marks by projection as shown in Figure 5.1. By changing the operating frequency of the actuator it is also possible to change the touch of the button itself and others. By doing this, I think that it can also express smooth touching when touching even the texture of wood.

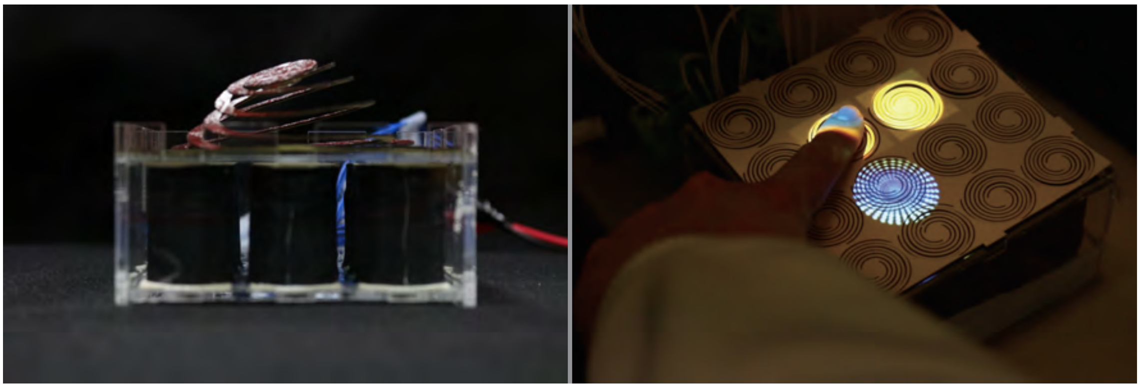

Figure 5.1: Left: The first application example of our shape-changing interfaces. It could be a button such as a power switch or volume controller. We can change the material of its surface into the leather. Right: The application for AR/VR that using our shape-changing interfaces. It projects the picture of the switch onto the surface of the actuator. It is able to response to the user's action such as touch or jesture.

5.1.2 Table Top Actuator

It is also possible to move an object on the actuator array using some cells or single cell. We created two types of Table top actuator that using 8×8 (64pins) larger electromagnets and 12×12 (144pins) smaller electromagnets. The sizes of them are 8×8 array which is 240mm width and depth, and 12×12 array is 189mm width and depth. The housing of small array is designed by 3D CAD software and printed by the 3D printer. It is easy to produce in large quantities for larger actuator array. Figure 5.2B shows the appearance of table top actuator that actuating the ball on the actuator. The actuator is driven by PC with web camera. The operator controls the actuator array while overlooking the actuator through the web camera. This application realizes the shape-changing interface without damaging to the surface texture. Furthermore, we are also able to wall type actuator.

This table top actuator is also used for the 2.5-dimentional display. This shape-changing interface does not have the right source. Therefore, we use the projection to indicate the information. It is able to point up the information by using this function for display. It realizes to allocate some functions to each actuator such as power switch or volume controller.

5.1.3 Wall Embed Application

In the conventional shape-changing interface, the thickness of the main body is very large and the weight of the main body is heavy so it has been limited to use on a desk placed on the floor. However, the shape changing interface proposed by us is much thinner and lighter than conventional ones. Therefore, it shows an image when the figure is placed on a figure which can be installed not only on a desk but also on a place where such an actuator could not be installed such as an inclined surface or a wall surface so far. By installing it on the wall surface, it is possible to realize interchangeable accessories etc. By replacing electric switches and the like attached to the walls of houses with this actuator, more unified design can be realized.

5.1.4 Design Consideration

When designing the interior and interior space, the designer reviews the materials as well as the interior design by the designer. When considering the conventional actuator to be embedded in a room, it is possible to embed an actuator with a targeted texture by using a desired material for the tip of the actuator. However, in this case, the cost of manufacturing the actuator increases, so it is difficult to change the material after the actuator is completed. The actuator proposed in this research is easy to exchange the material of the surface. Therefore, even if the designer wants to change the texture at the construction stage, it is possible to change the material of the surface to a totally different one by just processing a little. In this environment where prototyping is required, this method is effective. We believe that fitting of texture becomes possible by using the actuator manufactured by this method and the range of design will be wider than before.

5.1.5 Haptic device

Our actuator can also use for the haptic device. It could present the haptic feedback for the palm and some patterns of haptic feedback for users such as trace or scan. Our actuator is not damage to the texture when it is embedded to textured materials. It could attract attention to the actuator if it is embedded to the wall of the building or the table. We realized the function that could not only melt into the surface of surrounding material but also move when it needs to function.(Figure 5.2(Left))

5.1.6 VR and AR experience

Conventional application of AR/VR experience such as shooting game or simulation game are not able to cause the influence on the real world. We could not feel the feedback even if you defeat the AR object on the desk. It could not take enough experience to presence. When the player break objects in AR/VR world, the objects correspond to AR/VR world in the real world is also broken. We need to embed the actuator in our lives to this function in the real world. Therefore, we suggest the new ambient actuator to expand to AR/VR experience. For example, it is possible to express sounds and vibrations when destroying a shooting target with this actuator.(Figure 5.2(Right))

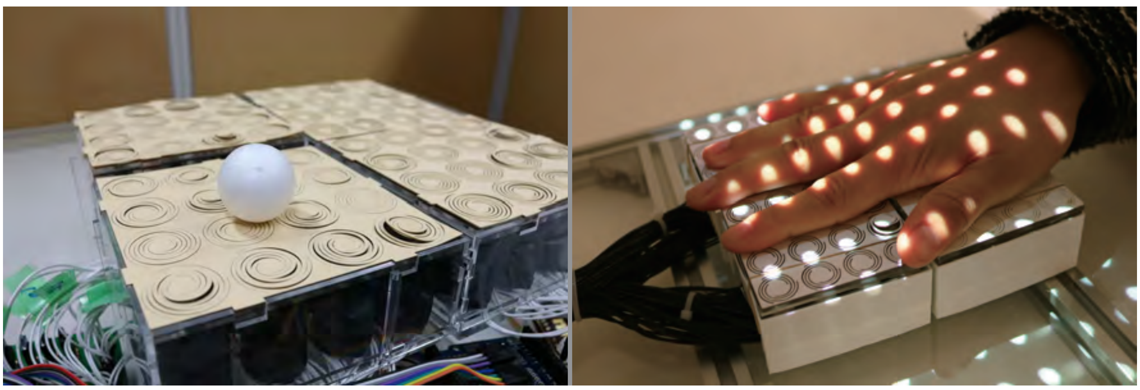

Figure 5.2: Left: The appearance of the table top actuator. It can control the movement of the small ball on it. Right: Our actuator can also use for the haptic device. It could present the haptic feedback for the palm.

5.2 Magnetic Levitation System

Next we will introduce applications using the floating object's center of gravity optimization method of the floating interface described in this paper. Conventionally, most of the magnetic levitation interface has been treated as a display device for shop front display. Application examples of the magnetic levitation interface using the barycenter optimization method proposed in this research are shown below.

5.2.1 Floating Display

The storefront exhibition by the magnetic levitation interface is carried out in part now. However, most of them are only to put the objects on the levitating magnets. In this exhibition method, the levitating magnets are visible to visitors and it is not good to look at. Therefore, by levitating the model to which the center of gravity optimization method developed in this research is applied, it is possible to magnetically levitate with a more natural appearance (Figure 5.3). Consider the levitation exhibition of model production with the case of using levitation exhibition as PR of merchandise of stores. First, 3D scans of products to be displayed are performed to form a three-dimensional model. It is possible to create an object that can levitate with a natural appearance simply by importing the three-dimensional scan data of the product into the center of gravity optimization system. Finally, if you ask 3D printing service with the generated model, storefront display using magnetic levitation can be realized. Those which are levitating will be able to pull out the eyes of the human being, so that shop front PR can be better than before.

Figure 5.3: Example using floating display for shop front display.

Chapter 6

Discussion

In this paper, we have described the center-of-gravity optimization method for the actuator using the magnetic force and the magnetic levitation system. In these user interface systems, we have developed thinner and more compact actuator systems than before and proposed a new storefront display system. However, these methods still have problems and issues to be solved. This section describes these problems.

6.1 Magnetic Actuator

We discuss the shape-changing actuator by the electromagnet mentioned in this paper. In the shape changing interface proposed by us, we realized the thinness which could not be realized with conventional actuators. However, there were some restrictions to get thin.

6.1.1 Range of Motion

The first problem is the problem of the range of motion as an actuator. The stroke of this shape changing interface is determined by the strength of the electromagnet and the strength of the permanent magnet. In an ideal environment, the strength B of the magnetic flux density is expressed by the following equation.

$$B = \mu_r \mu_0 n I \tag{6.1}$$

Here, n is the number of turns of the electromagnet, I is the magnitude of the current flowing through the electromagnet, μ_r is the relative magnetic permeability of the space, and μ_0 is the magnetic permeability in vacuum. From this equation (1), it can be seen that the magnetic flux density is proportional to the number of turns of the electromagnet and the magnitude of the current flowing through the electromagnet. To increase the strength of the magnetic force by the electromagnet, increase the number of turns or increase the current flowing to the electromagnet. In the shape changing interface proposed in this paper, the stroke is realized by using the repulsive force of the electromagnet and the permanent magnet. For this reason, the force actually acting between the electromagnet and the permanent magnet is reduced by leakage magnetic flux. In the current system, it is considered that a large stroke can not be secured because the repulsive force of the electromagnet and the permanent magnet is insufficient. In order to solve this problem, it is conceivable to simply increase the number of turns of the electromagnet to strengthen the magnitude of the magnetic force by the electromagnet. Also, the same effect can be expected by increasing the current flowing through the electromagnet. In addition, it is possible to strengthen the magnetic force on the side of the permanent magnet by making the permanent magnet larger than the current one. However, there are problems that these methods can not simply solve. In the method of applying a hand to the electromagnet, the amount of heat generated from the electromagnet increases and the casing itself may melt beyond the heat-resistant temperature of PLA. The heat resistant temperature of the 3D print material used in this research is 60 °C, so it easily melts with the heat of the electromagnet. Also, with the method of enlarging the permanent magnet, the actuator itself becomes large. For this reason, we implemented it under the conditions shown in this paper this time.

6.1.2 Balance of Actuator's Body

Another problem is the balance problem of the actuator body. In this method, the permanent magnets used on the surface of the actuator are not in contact with each other except that they are fixed to the surface material of the actuator. Therefore, when receiving a force by an electromagnet, it also receives a rotating force at the same time. A hard material like polypropylene or acrylic can prevent the force to rotate. However, it is not possible to prevent the force to rotate with a thin material such as synthetic leather or wood without hardness. As a result, the permanent magnet on the actuator surface side rotates and the shape of the actuator collapses. In this state, it becomes impossible to function as an actuator, resulting in a functional problem. In order to solve this problem, we think that this problem can be solved by attaching a thin and hard material like acrylic on the back side of a thin material such as synthetic leather. This increases the strength as the surface material of the actuator, so it is thought that it is necessary for mounting in order to paste the thin plate.

6.1.3 Shape of Slit

In this thesis, the triple helical structure is adopted as the material used for the surface material of the actuator. Various shapes were examined in conducting this study. We examined the spiral structure rather than the circle and the helical structure of the triangle but the circle helical structure has better workability and the circular spiral structure is adopted because it can take a large stroke. In a simple helical structure or a double helical structure, it is easier to rotate by losing the rotational force of the actuator as described above, so that the triple helical structure prevents the permanent magnet from rotating. In this study, I tried only the simple shape described here. Therefore, by applying detailed structural analysis methods such as the finite element method, it is considered that the structure can be determined by simulating the deformation beforehand. It may be possible to add functions like a slider in the horizontal direction as well as the vertical direction.

6.1.4 Resolution of Haptic Feedback

For now, the resolution of our shape-changing interface for haptic device is 8×8 pixels. From the experiment, we found it is not enough to present the precise tactile sensation. It is not difficult to made higher density of our interface because it depending on the size of the coils. We use the large size of coils now, so we can made higher density to use more smaller one such as flexible PCB (Poly Chlorinated Biphenyl) micro-coils [39].

6.2 Magnetic Levitation System

In this paper, we have proposed not only the shape changing interface using magnetic force but also the optimization method of the center of gravity of the object in the magnetic levitation device. In this method, balanced levitation was realized by matching the position of the center of gravity of the target object with the position of the center of gravity of the levitation magnet of the magnetic levitation device. In this method, we succeeded to levitate the 3D printed model in practice, but some problems that have to be solved still occur, so we will discuss them in this section.

6.2.1 Shape Restriction

In this thesis, 3D objects of Stanford bunny and banana shape were printed and confirmed to be able to actually levitate. In the three-dimensional object of Stanford Bunny realized the magnetic levitation in the simple case where the center of gravity of the object was originally inside the bottom. If the center of gravity is inside the bottom, you can levitate any shape. However, when the center of gravity is outside the bottom surface, optimization of the center of gravity may be impossible depending on the shape of the object. With a shape with a sharp bottom, you can not levitate under such conditions that the height of the model under the levitation magnet will be higher than the float height. Also, in a long and slender model like a snake, it can not be levitated depending on its shape. In this method, since floating magnets are buried at the bottom surface when levitating, the shape whose bottom surface is narrow and long in the height direction is difficult to levitate. It is a method to adjust the center of gravity to the target position while sharpening the model of the target object by voxelizing it. There is a possibility that the center of gravity position can not be adjusted to the target position even if the voxel is scraped off. Therefore, Make it stand makes it possible to optimize the center of gravity by deforming it without losing the features of the shape of the object. We believe that by adopting this make it stand method also in this method, we can expand the range of models to which our method can be applied.

6.2.2 Calculation Time

The problem of calculation time is also important. In this method, the model of the object is voxelized and processing is performed to reduce the amount of calculation. However, if the size of the model becomes larger or the size of the voxel becomes smaller, the calculation time becomes enormous. In this research, we are using Windows 10 Pro 64 bit, Intel (R) Core (TM) i7-8700 processor (6 cores / 12 threads / 3.20 GHz / TB maximum 4.60 GHz / 12 MB cache), 32 GB memory, NVIDIA GeForce GTX 1080/8 GB Processing was carried out using spec PC. Under this environment it took about 15 minutes for all bananas to be processed at 1 voxel 3 mm in length, about 15 cm in length, from importing the model into Grasshopper and completing all processing. If you set the voxel size to 1 mm under the same conditions, it will take more than one hour to process. It takes a very long time to process one model in this way. Although this is not so problematic for the realization of the function, it seems that it is easier for users to process at high speed. Therefore, we think that it is necessary to review the processing on python and grasshopper side to make the processing faster.

Chapter 7

Result and future work

So far, this paper has described the user interface using magnetic force. In this paper we have summarized the development of a shape changing interface that is thinner than the conventional one using magnetic force and has no constraints on the surface material. With the shape changing interface developed by this method, it is possible to replace the surface of the actuator, conventionally made of plastics or metal, with one with natural texture such as wood and leather. The material of the surface of this actuator is processed by a CO2 laser. We realized this function by digital fabrication technology which processes material according to puttern designed by computer. In this paper, prototypes with different sizes of 3 ×3 and 4 ×4 electromagnets were produced. These cells can be connected to each other and can be extended to large ones. In this paper, hardware verification and user study verification were carried out with the shape change interface produced. In the case of hardware verification, the response speed and the stroke as the actuator were measured. In the user study, we actually asked the user to touch the shape changing interface, and we investigated the texture and the texture of the appearance. Based on the results of the experiments, we considered that the shaping interface produced by this method is effective for applications such as button application and tactile presentation to the palm.

On the other hand, 2,000 coils were used to drive the actuator. We estimate that it is necessary to evaluate the characteristic change by changing the characteristics of the coil. We also estimate the shape of the surface material. Although triple helical structure is used on the surface, it is not enough to just consider processing pattern and processing method. Therefore, we need to do more experiments. Currently, we have created a 16 ×16 pixel electromagnet array. In the future, you will need to create a larger shape changing interface.

In addition to the shape changing actuators above, we proposed a method of optimizing the center of gravity of the levitating object in the magnetic levitation user interface in this thesis. In this method, the original model is voxelized and processing is performed so that the center of gravity of the model coincides with the center of gravity position of the target. With this approach, we were able to generate a magnetic levitable model for Stanford bunny and banana models. In the case of the Stanford Bunny model, we could implement with less calculation cost in the example where the center of gravity position is inside the bottom. In the banana model, it succeeded to levitate in various attitudes by changing the internal structure of the model, but the problem of increasing the calculation cost remained.

By actually using the interface system using these magnetic forces, we have been able to improve the function of the interface by shape change interface and magnetic levitation which had been limited in the scenes so far.

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