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Master's Thesis
Academic Year 2017

3D Printed Haptics: Creating Pneumatic Haptic Display Based on 3D Printed Airbags

Keio University
Graduate School of Media Design

Yuan-Ling Feng

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
MASTER of Media Design

Yuan-Ling Feng

Thesis Committee:

Associate Professor Kouta Minamizawa	(Supervisor)
Project Senior Assistant Professor Charith Fernando	(Co-supervisor)
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Abstract of Master's Thesis of Academic Year 2017

3D Printed Haptics: Creating Pneumatic Haptic Display Based on 3D Printed Airbags

Category: Science / Engineering

Summary

In recent years, Advances in the 3D print technology show us a way to customize almost anything we want.

In this paper, we provide a rapid fabrication method to create personalized pneumatic haptic displays using the 3D printing technology. Based on the miniature airbags, the haptic display is light to wear, waterproof, and low-cost. Because it is free to customize, various shapes even ungrounded(wearable) haptic displays or grounded haptic displays can be made out of. Each airbag is inflated by a full-range speaker which mounted on a closed air chamber where the air is transferred back and forth through a tiny nozzle to the airbag. So both low-frequency pressure and high-frequency vibration could be presented.

As a haptic display, the performance on rendering tactile sensation of the airbag was evaluated, also the psychophysical experiment was down for measuring the capability of rendering multi-dimensional tactile sensation. As the result, the airbag is able to present mechanical vibrations with a range of 2Hz to 800Hz, and to render directional tactile information which is correctly distinguished over 80%.

Keywords:

3D Printing, Fabrication, Pneumatics, Haptic Display

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Chapter 1
Introduction

In the digital age, there are some technical revaluations in the manufacturing process because of advances in computer-assisted design tools. one of them is the invention of Additive Manufacturing, a digital fabrication method also known as 3D printing. Different with the traditional manufacturing process which needs to cut the required parts from a larger raw material, it fabricates products by either depositing or binding raw materials into layers to form a solid, three-dimensional object. It's not only realized the Rapid Prototyping to improve the mass manufacturings speed, but also opened up a new world of personal fabricating. In recent years, 3D printing is become popular and allow people to make their daily things simply. We can have a vision that when 3D printer become a kind of household appliance, people are used to buying their favorite design file of products on Internet then downloading and printing it out immediately, rather than buying a mass processed product in a shop. Even if we can make a cup, phone case, band and more using 3D printer, we perhaps could make our haptic displays as the same way. In not-so-distant future, when you want to confirm the material in an on-line shop or try to stroke someone's head behind the screen, you just need switch on a 3D printer and print a haptic display which suits you.

1.1 3D Printing Technology

3D printing is a kind of digital fabricating method which can programmatically fabricate a static three-dimensional object. You can make almost anything you want through simple steps. 3D printing is not a new technology, it has been driven rapidly forward by advances in computing power, new design software, new materials, and the Internet. [12] The earliest 3D fabrication method was invented by Hideo Kodama of Nagoya Municipal Industrial Research Institute in 1981 [7]. Almost at same time, 3D fabrication is also growing up in American and Europe. In 1984, Chuck Hull filed his own patent for a stereolithography fabrication system [6], in which layers are added by curing photopolymers with ultraviolet light lasers. Hull defined the STL (Stereolithography) file format and the digital slicing and infill strategies common to many processes today. And then, start from 3D Systems Company has been started up in 1986, there are more and more companies which focus on this field have been built. Innovation on 3D fabrication methods was growing up on a fast speed. Diverse printing methods have their merits and faults and they will be described in next subsection.

1.1.1 3D Printer

Even all of the 3D printer has a unifying trait that they place raw materials into layers to form a 3D object deferring computer commands. The detail of how to deal with raw materials or how to solidify raw materials to a layer depends on the classification of a 3D printer. On a rough classifying, H.Lipson [12] explain that there are two major families of 3D printing technologies. The first family of printers deposits layers of raw material to make things. The second family of printers binds raw materials to make things. All types of the 3D printer can be classified into those two families. In this subsection, we would like to brief introduce three types(Figure1.1) of the 3D printer which is commonly used today to make plastic products. More details of the 3D printer can be find in the page from Additively[1].

Figure 1.1: Commonly used 3D printer for printing plastics[1]

Stereolithography (SL)

It's the earliest 3D printing method that process by which a uniquely designed 3D printing machine, called a stereolithography apparatus (SLA) converts liquid plastic into solid objects. An SLA machine starts with an excess of liquid plastic, some of which is cured, or hardened, to form a solid object. SLAs have four main parts: a tank that can be filled with liquid plastic (photopolymer), a perforated platform that is lowered into the tank, an ultraviolet (UV) laser and a computer controlling the platform and the laser.

In the initial step of the SLA process, a thin layer of photopolymer (usually between 0.05-0.15 mm) is exposed above the perforated platform. The UV laser hits the perforated platform, "painting" the pattern of the object being printed. The UV-curable liquid hardens instantly when the UV laser touches it, forming the first layer of the 3D-printed object. Once the initial layer of the object has hardened, the platform is lowered, exposing a new surface layer of liquid polymer. The laser again traces a cross section of the object being printed, which instantly bonds to the hardened section beneath it. This process is repeated again and again until the entire object has been formed and is fully submerged in the tank. The platform is then raised to expose a three-dimensional object. After it is rinsed with a liquid solvent to free it of excess resin, the object is baked in an ultraviolet oven to further cure the plastic.

Objects made using stereolithography generally have smooth surfaces, even oddly shaped objects, which can be difficult to produce using traditional prototyping methods could be created.

Fused Deposition Modeling (FDM)

It's a cheapest type of 3D printer we can get on market. This method builds parts up layer-by-layer by heating and extruding thermoplastic filament. Ideal for building durable components with complex geometries in nearly any shape and size, FDM is the only 3D printing process that uses materials like ABS, PC-ISO polycarbonate, and ULTEM 9085. This means FDM can create parts and prototypes with outstanding thermal and chemical resistance, and excellent strength-to-weight ratios. With our fast lead times and finishing options, FDM is a smart choice for anything from concept models to production parts. You even get a FDM type of 3D printer by DIY. There is an open source project could support you to make own 3D printer.

Polyjet Modeling(PJ)

It is a new technology based on inkjet 3D printing. Inkjet 3D printing, known variously as "binder jetting" and "drop-on-powder" or simply "3D printing" (3DP). An inkjet print head moves across a bed of powder, selectively depositing a liquid binding material. A thin layer of powder is spread across the completed section and the process is repeated with each layer adhering to the last. When the model is complete, unbound powder is automatically and/or manually removed in a process called "de-powdering" and may be reused to some extent. The de-powdered part could optionally be subjected to various infiltrants or other treatments to produce properties desired in the final part. The Polyjet 3D printer is use Inkjet print heads to jet liquid photopolymers onto a build platform. Then the liquid photopolymers are immediately cured and solidified by UV lamps.

1.1.2 Advantages and Potential of 3D Printing

Whatever which 3D printer you choose, the universal advantages of 3D printing technology listed below are effective with you.

- Easy to use. Less skill required than traditional artisan process and traditional manufacturing like injection molding machine.
- Variety and time-saver. It's a nimble tech to fabricate any kinds of things which can modeling in the computer. Time costs depend on the size of the object not on the complexity.
- Pre-assembly. 3D printer print things as an interlocked object, no assembly required after printing.
- Blend multi materials together. Combining different raw materials into a single product is difficult using today's manufacturing machines. Even blend soft material and hard material into a solid object.
- Precise physical replication. Even the whole object or parts of the object could be replicated precisely.

When creating a haptic display, above traits still benefit the fabrication process.

1.2 Haptic Displays

Haptic display is a display which could simulate touch sensation for human when human touching things which are not really exist here, and is generally used in

Virtual Reality, Teleoperation and Medical field. Haptic perception is a term of the sense of touch and means the sensibility of the individual to the world adjacent to his body by use of his body. Simulating touch sensation, in other words, means that recreates the sense of touch by applying forces, vibrations, or motions to the users' body. However, tactile and haptic are distinct in the field of psychology and HCI to represent these dimensions. According to ISO: Ergonomics of human-computer interactionPart910: Framework for tactile and haptic interaction (2009), haptic covers the area of tactile (the sense of touch) and kinesthetic (the sense of body position or movements) [35]. Force display that kinds of devices could provide a strong force which can control body movements for the human body to give human kinesthetic feedback also be classified under the haptic display. But in this paper, we distinguish haptic display from force display, and discuss haptic display in a narrow sense, a display to provide cutaneous/tactile feedback.

1.2.1 Touch Sensation of Human

Before introducing the background of the haptic display, we'd like to introduce the mechanism of human touch sensation in this section. When human touching something, the cutaneous receptors found in the dermis or epidermis will be stimulated and then transmit the electric signal to the brain. Cutaneous receptors include nociceptors, thermoreceptors and mechanoreceptors. Nociceptors that responds to damaging or potentially damaging stimuli by sending possible threat signals to the brain and thermoreceptors that responds to relative changes in temperature are wouldn't be described. Our research only generates pressures or vibrations that types of mechanical stimulation to stimulating mechanoreceptors. Human receive mechanical stimulation from four types of mechanoreceptors listed as following:

- Merkel cell (SAI), are oval-shaped mechanoreceptors essential for light touch sensation and found in the skin of vertebrates.
- Meissner corpuscles(RAI), underlies the perception of flutter and slip on the skin. They have small receptive fields and produce transient responses to the onset and offset of stimulation.
- Ruffini endings(SAII), respond to skin stretch, but have not been closely linked to either proprioceptive or mechanoreceptive roles in perception.

They also produce sustained responses to static stimulation, but have large receptive fields.

- Pacinian corpuscles(RAII), underlie the perception of high frequency vibration. They also produce transient responses, but have large receptive fields.

The four types of mechanoreceptors not only morphological differently, but also different on kind of sensation they perceive, the rate of adaptation and the receptive field. In Figure1.2, the characteristics of four mechanoreceptors which important for haptic simulation is summarized by [35].

	Merkel discs	**Ruffini endings**	**Meissner corpuscles**	**Pacinian corpuscles**
Property	SA Type I	SA Type II	RA Type I	RA Type II
Sensation	Pressure	Stretch	Tap, flutter	Vibration
Frequency	0.4-1, 5-15	150-400	25-40	200-300
Field area	Small (12.6)	Large (101.0)	Small (11.0)	Large (59.0)
Adaptation	Slow	Slow	Rapid	Very rapid

SA: Slowly-adapting, RA: Rapidly-adapting

Figure 1.2: Different type of mechanoreceptors [35]

1.2.2 Grounded and Ungrounded Haptic Displays

The haptic display can be classified as grounded and ungrounded haptic display based on their workspace. The methods to creating grounded haptic display are different with the methods to creating ungrounded haptic display as usual. But the method to create both grounded and ungrounded haptic display is exited.

Grounded haptic displays

The grounded haptic display is placed in space and without keep contacting with the human body. There is tow kind of grounded haptic display, one is grounded but require direct skin contact, like rendering tactile feedback on a touchscreen or active surfaces that enable direct exploration and palpation of dynamically varying shapes. The other is mid-air haptic interface that enables both direct-touch and mid-air interaction, without the direct contact with the human. The way to render texture feedback on a touchscreen is that uses electrovibration to representing the change in friction [24], or utilizes magnetorheological fluid (MRF) which is flexible liquid affected by the magnetic field, and electrovibration on a film that covers MRF to generate adsorption force from the electrostatic field [4]. Active surfaces that try to literally re-create the object that is being touched are a brute-force approach to haptic display. They are also shape displays that allow tangible input. There are two successful approaches, one uses pin array which renders 3D models physically, allowing for many points of contact and un-tethered interaction, like [10]. These types of shape displays remain limited by their linear actuators and the fact that they are often large table scale devices due to the size of actuators. the other is deformable crust topologies like [29] use particle jamming enable continuous surface. Mid-air haptic feedback can be realized with air laser [27] or ultrasound speakers [29].

Ungrounded haptic displays

Ungrounded haptic display also could be called as wearable cutaneous display, because they are worn on a body part or held on hands and provide tactile feedback by stimulating skin directly with miniature actuators, and eliminate typical workspace restrictions of haptic feedback [18]. Ungrounded haptic display usually creates for fingertips which are the body parts used to touching objects. The hardwares often used for creating ungrounded haptic display include DC motor and voice coil actuator. Some devices operate on the finger pad by translating and orienting a small mobile belt or platform DC motor driver like [14] and [11], or voice coil driver [28]. Pin array also can be used on ungrounded display, like [2] embedded pin array platform into a game controller. But as we said, the bulky actuation system limited the portability of pin array type haptic display. 16 server motors are used for driving the 44 array of pins in this work, it proves the difficulty of making a pin array type of wearable device.

1.2.3 Possibility of Fabricating Various Haptic Display

Almost previous haptic displays are designed for specific body parts or situations. So their fabrication methods are hardly used for redesign the haptic display for another body part or situation. Besides those, there is a kind of haptic display are easy to be made as various shapes pneumatic haptic displays. Because of its soft body is separated with the electro-mechanical inflating system, the shape of the soft body which contacting with the human body are free to be redesign. But pneumatic haptic displays which made out with previous methods have some defects. Firstly, they are difficult to be integrated with a hard component. Secondly, their fabricate process need artisan skills and need time. Those defects are limit the variety of previous haptic displays and impossibly provide a customized haptic display for amateur users. Also the previous inflation system uses air pump to inflate the pneumatic body, restricting the range of frequency that display can present. The detail of previous pneumatic haptic display will be discussed in next chapter.

1.3 Research Purpose

In recent years, consumer VR devices are being popular, and then bring the requirement of the personal haptic display. Previous haptic displays almost have a complex structure and bulky body, even pneumatic haptic displays which are light and customizable have a skill required fabrication process. So previous methods couldn't provide a server to making a customized haptic display for general users. Aiming at this defect, 3D printing as a less skill required and rapid fabrication method with high customizability is a good solution for fabricating a haptic display. What's more, as advancing on personal fabrication and requirement of the haptic display, a common fabrication method of personal customizes haptic display is needed.

This research proposes to provide a common fabrication method of creating a pneumatic haptic display using 3D printing technology. Either grounded haptic display or ungrounded haptic display could be made out through the same method.

1.4 Thesis Outline

This thesis is divided into six chapters, and each chapter is listed below:

- Chapter 1 introduced some backgrounds of tow basic technology that related to this research, 3D printing technology and haptic technology. Then point out the purpose of the research.

- Chapter 2 describes the related works and analyses their pluses and minuses to light up the stand point of this research.
- Chapter 3 discusses the design of airbag and lists the modeling and fabricating process.
- Chapter 4 describes the implementation process of whole inflation system.
- Chapter 5 measures the limitation and specification of the airbag as a haptic display, and evaluates it's performance on two and three of degree of free.
- Chapter 6 shows completed application of the haptic display.

Notes

1 `https://www.additively.com/en/learn-about/3D-printing-technologies`

Chapter 2
Related Work

In this Chapter, we will talk about closely related works classified under three backgrounds. First is the previous works that used the 3D printing technology, and second is the previous pneumatic haptic displays which are fabricated via various methods. At last the methods to render tactile feedbacks is discussed.

2.1 3D Printed Work

3D printing could bring your stereoscopic design from a computer into the real world, and it simplifies the DIY(do-it-yourself) process for designers who use digital design tools to creating things. The multi-material output shows us more possibility. Except articles for daily use, suitable clothes, biologic organizes, architectural small scale models, conductive electrical layers and more are available for 3D printing. Advances in 3D fabrication bring many changes on manufacture process of design, art, fashion, architecture and medical fields. One more exciting thing is that some works show us ways of fabricating interactive objects combining with custom sensors and actuation components.

2.1.1 3D Printed Static Objects

The common usage of the 3D printer is 3D printing a static object which is completed in computer modeling. As a manufacturing tool, the 3D printer is most popular in design and art field and stirs some innovative projects. For example, Nervous System[1], a company uses 3D printer for fabricating produces which have special complex forms and don't have a fixed outcome. Instead design products, they translate natural processes into computer algorithms for crafting generative design system that results in a myriad of distinct creations(Figure2.1). 3D printers are not only used fabricating the small products, but also used for creating large scale objects like architecture. Digital Grotesque Project[2] from Michael

Hansmeyer takes additive manufacturing technology to a true architectural scale not small scale models.

Figure 2.1: 3D printed static objects produced by Nervous System[1]

2.1.2 3D Printed Interactive Objects

Except using the 3D printer for printing pre-assembly static objects in their entirety, we would like to introduce some works that providing 3D fabrication methods for getting more dynamical, controllable and functional outcomes. There are some special ways of using the 3D printer for fabricating interactive objects, like Printed Optics [32] uses transparent materials for creating custom optical elements for interactive devices(Figure2.2 Left). And it enables sensing, display, and illumination elements to be directly embedded in the casing or mechanical structure of an interactive device. Savage et al. [25] presented a tool for routing and optimizing pipes within 3D printed structures, which can support a range of pipe-based interactive objects shown in Figure2.2(Right).

Figure 2.2: 3D printed interactive objects. [Left: 3D printed optics. Right: 3D printed and tube based interactive objects]

3D printed pneumatics

One kind of interactive objects is actuated with pneumatic actuation mechanism which closely related with our research. Some of them are don't have inner electronic components and only support one kind of interaction. Like Blossom from Richard Clarkson[3] shown in Figure2.3 left, it prints a flower which blends of two materials with varying physical properties transitioning from flexible to rigid and forcing air into the cavities of the flower causes it to bloom. The others are combined with electro-mechanical components to realizing interaction. For example, [26] present a method for rapidly prototyping interactive robot skins using flexible 3D printed material and analog air pressure sensors. They sense air pressure in chambers passively to prototype particular manipulation affordances on robot skins. Another example from Vázquez et al. [31] also printing pneumatic objects have an air pressure sensor in their interior but actively to provide haptic feedback or render computational states. They use 3D printer creating pneumatic controls whose haptic feedbacks can be manipulated programmatically through pneumatic actuation(Figure2.3 Right). In particular, by manipulating the internal air pressure of various pneumatic elements, they can create mechanisms that require different levels of actuation force and can also change their shape. Similar to our approach, They discuss a series of example 3D printed pneumatic controls which include conventional controls, such as buttons, knobs, and sliders, but also extends to domains such as toys and deformable interfaces. The main difference with our work is that they purpose to creating pneumatic input devices with several levels of activation forces for inputting with haptic feedback, rather than provide an output haptic display with wide bandwidth for simulating texture or force direction.

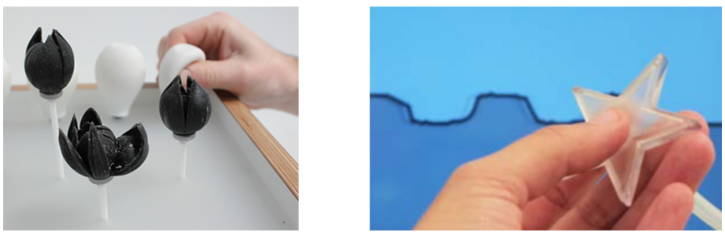

Figure 2.3: 3D printed pneumatic objects[Left: Blossom from Richard Clarkson. Right: 3D printed pneumatic input controls from Vázquez et al. [31]]

2.2 Pneumatic Haptic Display

The haptic display was briefly introduced in the previous chapter, in this section, pneumatic haptic display that the most related kind of haptic display will be introduced in details.

In one side, parts of researches focus on using pneumatic materials to rendering tactile sensation via two approaches. One fabricates the pneumatic actuator which consists of a serial of miniature air chamber arrays. Those researches are used to give haptic feedback on the most sensitive body parts, fingertips. For example, [17] used silicon to make out the chamber arrays, see Figure2.4 left. Except for use inflation pressure to stimulating the mechanoreceptors through skin deformation, researches like [13] and [5] using suction pressure to achieve the similar goal, shown in Figure2.4 right. The other is uses big airbag which has low-definition

Figure 2.4: 3D printed pneumatic objects[Left: Haptic display using air chamber array. [17] Right: Haptic display using air suction force. [5]]

but could provide powerful pressure. Those kind of displays are suited attaching on bigger body parts for providing user with spacial information to navigates, like a waist-type Hanger Reflex navigation system [8](Figure2.5(A.)) and Sarotis Project[4](Figure2.5(B.)) that a set of airbags which is worn on arms, legs, and waist to providing users with room interior spacial information. As well as WRAP [21], a wristband type pneumatically actuated haptic guidance with four airbags shown in Figure2.5 (C.). What's more, KOR-FX gaming vest[5] that a vest type pneumatic haptic display for enhancing game experiment is already appear on the market. On the other side, pneumatic materials are usually used to make shape-change interface that a kind of tangible interface implying haptic feedback. Those researches whose main point is diverse outcomes of the fabrication method are able to create both a tangible interface with haptic feedback and a haptic display consist of air chamber array. But they didn't further discuss applying on haptic rendering. For example, [34] fabricate air bubble arrays whose each

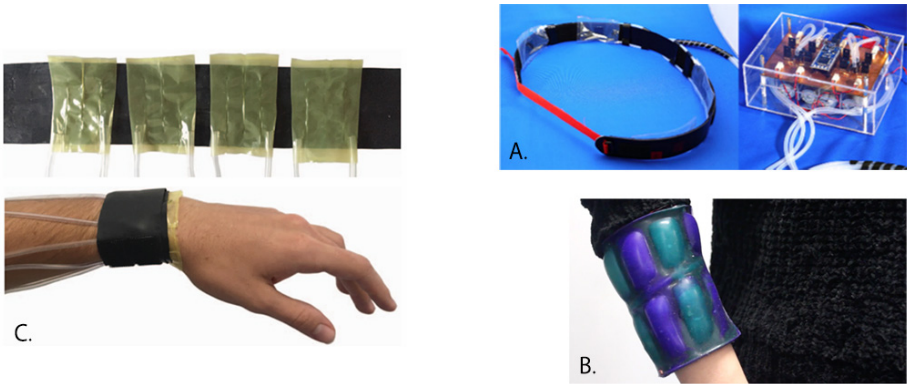

Figure 2.5: Pneumatic haptic display used fro providing directional information[A: A waist-type Hanger Reflex navigation system. [8] B: Sarotis Project. C: WRAP. [21]]

column can be inflated separately inside silicon. Similar to an active surface, the texture information of silicon surface can be varied by pumping and vacuuming air in separate columns at different times(Figure2.6 Left). Another example shown in Figure2.6 middle, Ou et al. use heat-sealing inflatable shape-change materials fabricating haptic gloves that contain small air chambers on the palm side and are controlled by a single air source [19]. The haptic feedback from this gloves is the air pressure actuated with an air pump. Also miniature air chamber as a shape change interface can be mounted on touchscreen to augment its haptic feedback, such as Russomanno et al. [23] using pneumatic bubbles to create physical buttons which shown in Figure2.6 right.

Figure 2.6: Pneumatic shape change interface used for haptic display. [Left: A silicon surface contains air chamber arrays. [34] Middle: A haptic glove uses heat-sealing airbags. [19] Right: Pneumatic bubbles to create physical buttons mounted on touchscreen. [23]]

2.3 Tactile Rendering

The purpose of haptic displays is to simulate the texture and shape of a object and render tactile feedback for the user. So the usability and practicability of a haptic display to a great extent based on its ability to render tactile feedback. Tactile sensation can be described as a sense of perceiving the texture that includes roughness, softness, and friction of objects, as well as perceiving vibration, pressure, and friction from cutaneous. The texture of objects is usually simulated via generating vibration waveform. And directional information which for higher degree of freedom is provided by single-point-contacted torque which via DC motor-based mechanism or multi-point-contacted spatially distributed forces.

2.3.1 Vibration-Based Texture Rendering

Some researchers use mechanical vibration to alter friction of display surface [3], and create the illusion of bumps and valleys based on the lateral force [16]. Electrovibration system is wildly used for rendering electrostatic tactile feedback on a grounded haptic screen that allows the user moving their finger to explore the surface features such as TeslaTouch that a electrovibration display combined with an interactive display and touch input, it enables the design of a wide variety of interfaces that allow the user to feel virtual elements through touch. presented by Bau et al. [1]. Researches such as [33] shown the method of displays roughness using electrostatic force to change the friction on fingertips. Except for those small texture, according to Saga et al. [24] large bump that presents geometrical information is can be rendered via the lateral force based vibration.

The other way which is simply but effective to generate rich vibration information is based on recording. In this kind of rendering method, usually use accelerometer to recording texture information then rendering texture feedback via a voice coil actuator. The structure of a voice coil actuator is simple. In its center, a donut-shape permanent magnet is located. A coil (a voice coil) is then inserted in the hole. When an electrical signal passes through the coils wire, the voice coil moves back and forth. The sides of this voice coil are attached to flat thin panels, and thus the actuator will produce vibration corresponding to the original input electrical signal. For example, Kuchenbecker et al. [9] used accelerometers to record contact vibrations between surgical tool and human organs. And Romano et al. [22] discussed a realized solution for creating realistic virtual textures from contact acceleration data. There is another recording method that using microphone to record sound signal as a vibration waveform, such as Minamizawa et al. [15] which created a device to record vibration signal from a microphone and transmit it to actuator in real time.

2.3.2 Directional Tactile Rendering

Most of conventional researches about vibratory texture display which employ voice coil motors limited the direction of vibration to one degree of freedom. Since a single voice coil motor cannot validate the effect of direction of vibration. Previous methods to rendering directional tactile feedback are include employing direction-controlled mechanical vibration based on multi motors and strings [24], employing spatially distributed force on fingertip [5], and generating reliable torque on fingertip via motor control movable plane [11] [20] [28].

Notes

1 `https://n-e-r-v-o-u-s.com/projects/`

2 `http://www.michael-hansmeyer.com/projects/digital_grotesque.html`

3 `https://www.richardclarkson.com/blossom`

4 `http://www.interactivearchitecture.org/sarotis-the-new-sense.html`

5 `http://www.korfx.com`

Chapter 3
3D Printed Airbag

The atoms to make up of this pneumatic haptic display is the 3D printed airbag. This chapter will describe the concept of the airbag design, and the details in the whole fabrication process. Based on the same fabrication method, various shapes of the airbag could be created and be used for diverse applications.

3.1 Concept

To provide a rapid fabrication method of creating customizable pneumatic haptic display, we propose a fabrication process that based on creating the miniature 3D printed airbag which is scalable to fit up with different requirements and light to wear. The 3D printed airbag that combines multi-materials with different softness is not only customizable for users via digital fabrication tools but also gives a possibility to make shapes that traditional manufacturing couldn't produce. Except for the shape, the number of airbags to constitute a haptic display also controllable, that allows a haptic display to rendering spatially distributed force. What's more, the haptic display can be used underwater because of its non electro-mechanical structure. If we can make a reliable haptic display through 3D printing technology, people are able to get a suitable haptic display for their own via a low cost way.

3.2 Functional Design

For fabricating diverse haptic display and allowing general users to customize their own haptic display, a less skill required modeling process with high customizability to make a 3D printed airbag is expected. The 3D printer is a less skill required toll, but the quality of product printed out is still depends on maker's 3D modeling skill. So we try our best to simplify the modeling process for providing a beginner-friendly method. The 3D printed airbag as a basic element to constitute a nimble pneumatic haptic display, should be designed on following principles:

1. inflated with appointed chamber and prevents any air leak.
2. small enough to be worn on small body parts like fingertips.
3. light enough to be expanded into multi body parts.
4. could be extended to fit larger body parts.
5. only deforming the surface contacting with human body when being inflated.
6. scalable and customizable.
7. durable.

3.3 Design Details and Fabrication Process

In this work, we used the Autodesk Fusion360[1] software for modeling the airbag and a Stratasys Objet260 Connex3[2] multi-material printer which is a kind of Poly-Jet printer for printing the airbags. PolyJet which belongs to ink-jet technology is a 3D printing technology that jets layers of liquid photopolymer as thin as 16 microns (0.0006) to build models and prototypes with extremely complex geometries, fine details, and smooth surfaces. Autodesk Fusion 360 is a CAD software which could build modules from 2D sketches. It gives a possibility that building 3D model just needs simple drawing skill. There are three kinds of materials are available for the 3D printer: tow hard materials named RGD(white) and Verob-lack(black), a soft material named Tango+. A feature of the 3D printer is that it could output materials which mix two different materials together according to an appointed percentage. According to the principle 5, airbags need contains two main manufacturing parts ,soft rubber surface and hard rubber shell to hold the shape. In order to reduce the overall size of the airbags, a 1.8mm outer diameter transparent air tube was used. The corresponding nozzle was built on to the hard shell so that it does not require any off-the-shelf valves. We were keeping attention with the design principles, then make out the available prototype by trail and error. There are tow prototypes will be described in details.

3.3.1 Prototype 1

As our first successful trial out, this kind of airbags assembles the Veroblack (hard rubber shell) and Tango+ (soft rubber outer) component together. It was designed for fingertip and was possible to create an airbag with single face inflation/deflation while mounting the hard shell to an existing object or fingertip. Tow versions are made out and both made for the fingertip. One is single airbag version(Figure3.1) that can present one DoF haptic feedback.

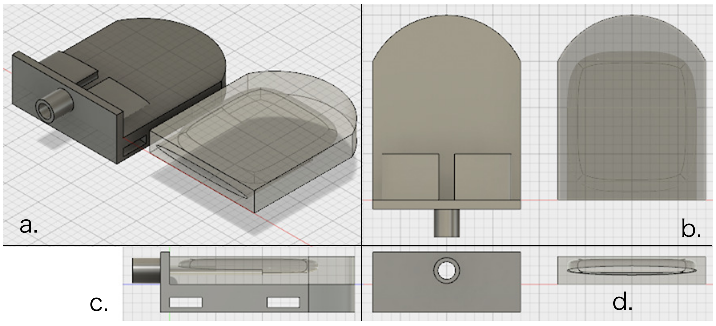

Figure 3.1: Single version airbag (a) Perspective, (b) Top, (c) Side, (d) Back view on Autodesk Fusion 360

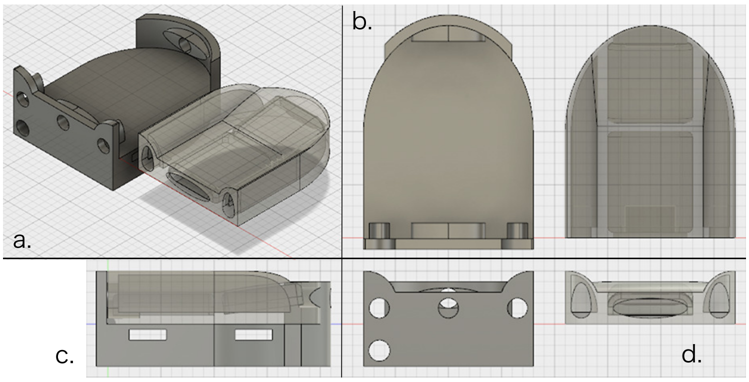

Figure 3.2: Spatial version airbag (a) Perspective, (b) Top, (c) Side, (d) Back view on Autodesk Fusion 360

the other is spatial version(Figure3.2) that designed for presenting 3DoF sensation. The soft outer can be slid through towards the hard shell so that it will complete the soft airbag component. About the modeling procedure, the plane sketch of the airbag is drawn first, then the soft component is pushed up from sketch before hard component, cutting out the air chamber which is insides of the soft component carefully as the next step, finally, carving the hard shell to plug the mouth of soft component.

Figure 3.3: Completed prototype 1

The prototype printed with this method is shown in Figure3.3. The central one was so small such that 4 miniature airbags could be embedded into single fingertip. The distance between two airbags was designed as a minimum of 1mm as the human can only identify two-point discriminable distance when the point of interaction becomes 1mm to 2mm [30]. It's also possible to inflate/deflate all 4 airbags and stimulate as a single point touch. The air flow has been taken into consideration when designing the 4 airbags such that front bag's air flow is routed via the side of back airbag. This was it was possible to attach the tubes only to the back side of the fingertip display, but to route the air-flow whenever needed to any location.

Through the simple evaluation, some problems of this prototype are found out. Firstly, there is a little air leak. Secondly, the surface not contacting with skin have a possibility to be deformed. Thirdly, make sure the contacting surface of the airbag is not easy to be broken. Fourthly, the support materials filled up chambers of the airbag are hard to be cleared up.

3.3.2 Prototype 2

To solute the problems found in Prototype 1, the new design of the airbag is developed. We simplify the design process for easier redesigning, and ensure the new prototype does not leaking air. A typically modeled standard new airbag is shown in Figure 3.4, it consists of a multi-material main body which is printed pre-assembly and a hard thin cover which need to be assembled after printing. The main body combines three layers together. Only the surface where the human skin will attach needs to be deformable, so there is one layer made out of soft materials. The other layers should be made out of hard materials for concentrating air pressures on the soft layer. Furthermore, the hole which connects with an air tube should be opened on a solid surface to avoid the air leak. Thus, as indicated in the Figure 3.4, the airbag is printed as two individual components. One is a multi-material main body consisting of three layers: a soft surface which contacts with the skin on the top, a hard frame which connects with the tube at the bottom, and a mix-material(70% RGD + 30% Tango+) transition frame in between for combining the soft layer and the hard layer tighter. The other is a hard cover that needs to be assembled using Epoxy resin adhesive after printing. We adopted this mechanism of printing the airbag as two separate components to avoid building up of support materials inside the vacant area when printing hollow objects. The

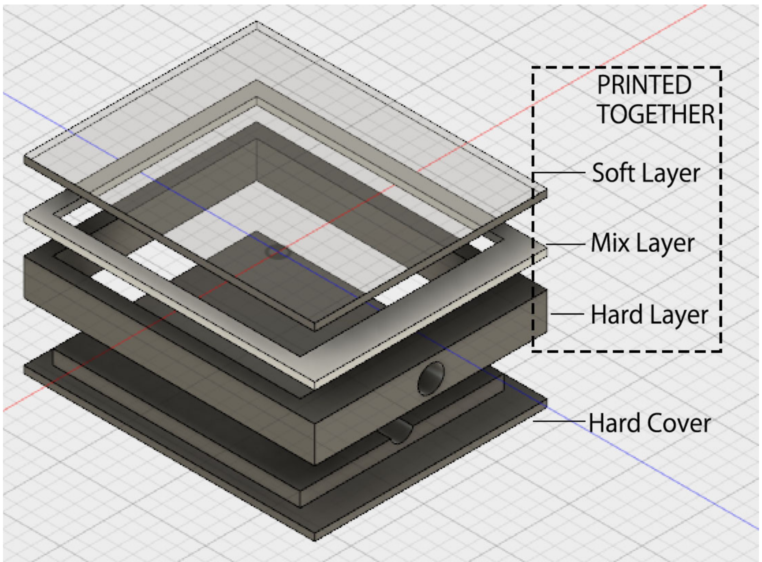

Figure 3.4: Exploded design view of the structure of the airbag's basic pattern.

modeling process in Fusion360 is summarized as three steps: 1) Draw the shape of the airbag: In the 2D sketch plane, draw an outline and a inner line to construct the shape of the airbag you want. 2) Extrude each 3D components from the sketch plane: There are two guidelines for pushing out the hard layer and the soft layer. One is that the hard layer (Figure 3.4) should be 0.7mm greater than the outer diameter of the tube to avoid weakened structures near the hole. Next the thickness of the soft layer (Figure 3.4) is recommended between 0.1mm and 1.0mm. The soft layer thickness under 0.1mm could easily rupture during repeated actuation use and thickness over 1.0mm would require more powerful actuation system. 3) Arrange the position of each component according to the basic structure of the airbag as shown in Figure 3.4. Except the cover component, other components that construct the main body of the object should joined in order.

Moreover, I would like to share the whole modeling process of the basic pattern in detail as follows:

1. Draw the inner line of the airbag. Drawing closed lines to the shape which you want the airbag to be in the 2D sketch plane. Then a surface drawn with the inner line is created.

2. Draw the outer line of the airbag. Copying and scaling up inner line to where 10mm far away as the outline of the airbag. Then another surface drawn with the outer line is created.

3. Extrude the hard layer and dig out the tube hole. Select the outer line surface in the sketch plane then extrude the hard layer to a 3D component which higher than 2.5mm. Because the tube hole which will be dug out is 1.8mm in max diameter, we need to ensure it wouldn't crashing down the hard layer. This component is the frame which will be made out of RGD450 to hold the airbag's shape. The hole should be designed as a cylindrical shape whose inside area smaller than outside area for connecting to the tube tightly.

4. Extrude the mix-material transition layer. Select the outer line surface in the sketch plane, then extrude a 0.5mm layer which will be made out of (a material mix up with RGD95% and Tango+5%).

5. Extrude soft layer. Select both of surfaces in the sketch plane, then extrude the soft surface with thinness between 0.1mm and 1.0mm. The three

components of main body are completed.

6. Extrude a cover. Select both of surfaces, then pushing out a thin layer around 0.1mm. For easier assembling this cover with main body, selecting center surface and pushing out a 1mm component joint with the thin layer. Moving this cover under hard layer.

7. Arrange the position of each component. Move the cover to the bottom of others components. Move the soft layer up the transition layer, and the transition layer up the hard layer. Because the three layers are printed pre-assembly, they need adjoin each others.

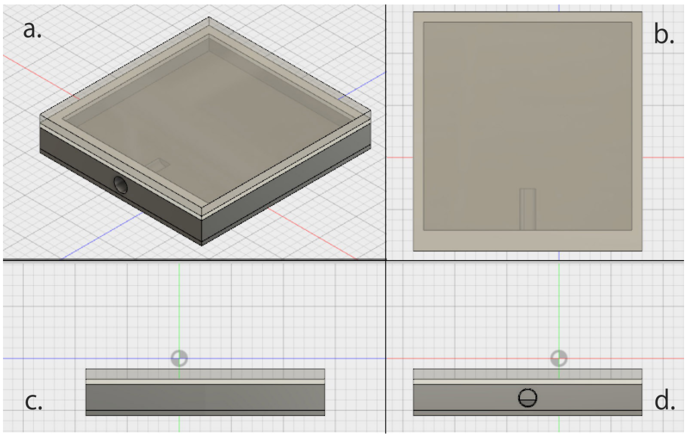

Figure 3.5: Basic pattern airbag (a) Perspective, (b) Top, (c) Side, (d) Back view on Autodesk Fusion 360

After the 3D modeling process, we can print the models out. In this printing process, we print the airbag which is separated to two components and assemble components together to get a final product. The basic pattern airbag which is shown in Figure3.5 also is selected to describe the printing process as following steps:

1. Export 3D models to STL files. Each layer must be exported to individual STL file, so one airbag contain four STL files.

2. Import STL files to the 3D printing software named Objet Studio. Three layers which are constitute the main body need to be selected together when import them into Objet Studio. Remember to mark the checkbox of "Assembly" before clicking the import button.

3. Change the material and placement of 3D models in Objet Studio. As we introduced, the main body of an airbag is consists of three layers with different materials. Select layers which will be made out of the same materials, and change their default material to the expected material. After finishing the material setting, put the models to suitable place. The important point of printing the main body is the soft layer need to be put downward and the hard layer need to be put upward, that for printing the main body without filling up with support materials. The hard cover should be printed while its wide side downward.

4. Print models out and wash the support materials off.

5. Assemble two components together to get the final product. Epoxy resin adhesive is used for sealing up main body and cover.

The airbag printed out is shown in figure3.6, that can be inflated to various levels.

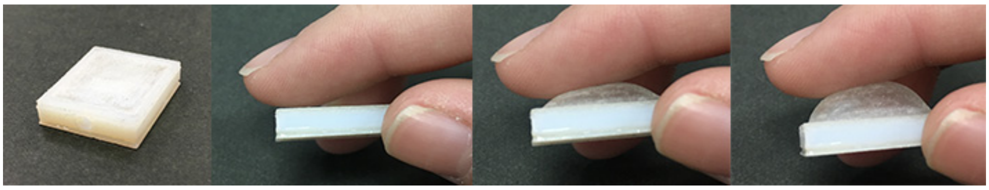

Figure 3.6: The soft surface inflated to various levels by pressuring the air bag.

3.4 Variations

With the 3D printing technology, the pneumatic display based on the airbag is easy to be designed for personalized sizes and various shapes, which was not easy to be realized before. The modeling method provided in this research allows users to redesign and revise the haptic display easily. All you need to do is just revises the sketch drew in the first modeling step, then the shape of the airbag will be changed correspondingly by Fusion 360.

Based on the basic pattern which is explained on the previous section, we created several types of haptic displays which could be used in different applications. The first type is a wearable display such as Figure 3.8 C which is made for the

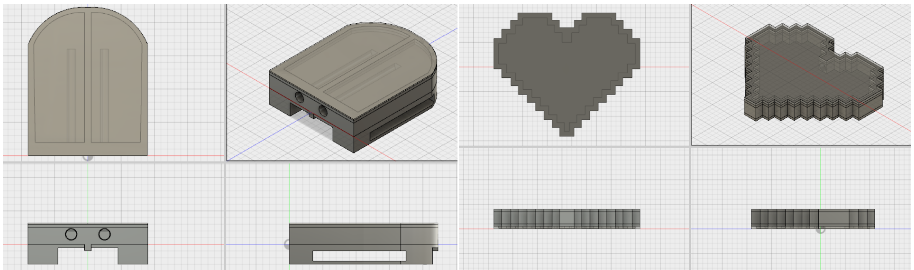

Figure 3.7: Changing sketch to get customized airbag. Fingertip 2DoF Pattern(Left) & Pixel Heart Pattern(Right)

fingertip. Fingertip patterns consist of a single airbag to present one-dimension force, or multi airbags to present multi-dimension force. Among all the haptic displays made by us, the one having max DoF consists of four airbags, which can present 3-DoF force. The second type is built into tangible objects such as the heart shown in Figure 3.8 B, where the objects are designed as meaningful shapes. Also arraying multi airbags in Fusion 360 to merge as a multi-cells active surface like Figure 3.8A is possible. However, another way to create the haptic display is embedding the airbag into the existed 3D models. For example, as shown in Figure 3.8B, adding a heart shape airbag into a bunny to let a static object become a dynamic haptic display. The heartbeats make bunny toy vivid. In addition to embedding haptic displays, if an airbag is added to some joints of a 3D model, it could actuate movements of parts of the model. For example, the dolphin's (Figure 3.8 B) tail joint is embedded with an airbag, so that the tail will waving during actuating.

3.5 Applications

Trough the variations of the 3D printed airbag, it can be applied as an ungrounded cutaneous display, a grounded active surface, or a tangible haptic display. The wearable cutaneous displays worn on fingertip and wrist are designed as example. The light airbag is free to be duplicated and extended to five fingers. Also a gloves type display for whole hand is possible to be made out of. Active surfaces we introduced in Chapter1 has a approach that using pneumatic particle jamming cells. Similar with that, arraying multi airbags in Fusion 360 to merge as a multi-cells active surface is possible. The tangible haptic display here means a physical object which has own affordance and is added haptic functions to. Like the heart

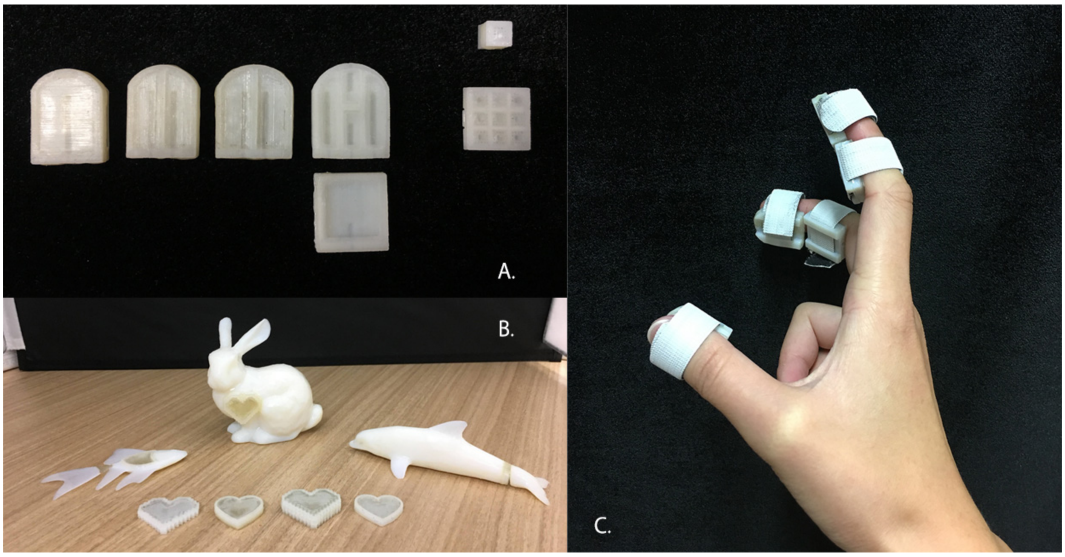

Figure 3.8: Various designs of the haptic display(A. Wearable haptic displays for fingers and ungrounded haptic displays consisting of an array of air chambers. B. Tangible objects embedded with airbags. C. Wearing the haptic displays)

pattern airbag or the bunny toy with heart airbag which is shown in the previous section. This kind of haptic display conveys haptic information through both air vibration and their shapes. What is means even the airbag is actuated by a same frequency, the feedback could represent bunny's heartbeats or fish's breath depends on where is it attached on.

Notes

1 `https://n-e-r-v-o-u-s.com/projects/`

2 `http://www.michael-hansmeyer.com/projects/digital_grotesque.html`

3 `https://www.richardclarkson.com/blossom`

4 `http://www.interactivearchitecture.org/sarotis-the-new-sense.html`

5 `http://www.korfx.com`

Chapter 4
System Implementation

In the previous chapter, the actuator was described in details on the design and fabrication process. To present haptic feedback, a actuation system for inflating and deflating the 3D printed airbag is implemented. In this chapter, the whole system including the system design and the actuation mechanism which contains hardware and software will be explained.

4.1 Entire System Design

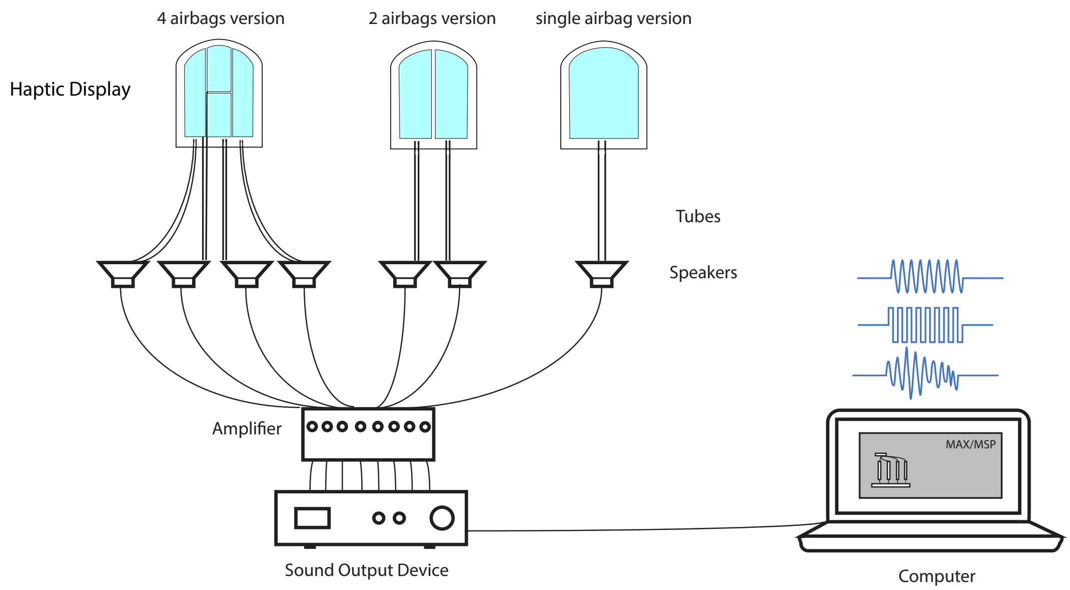

Figure 4.1: System overview

As shown in Figure 4.1, the system consists of three main components. 1) The actuator that consists of a single airbag or multi airbags 2) A speaker based actuation mechanism to produce the air pressure waves to actuate the airbags. Each speaker is attached to an independent audio channel on an eight channel amplifier board which was used as an interface to convert the pre-amplified signal to the speakers from a multi-channel USB audio interface (Roland - OCTA-CAPTURE[1]). 3) A personal comptuer (PC) for generating the necessary low and high frequency audio waveforms to drive the speaker based acutation mechanism. For the purpose of this prototype we utilize the Max MSP software to generate the audio wave forms.

4.2 Actuation System

The actuator is introduced in the previous chapter, then details of the actuation system will be explained from aspects on the hardware and software.

4.2.1 Hardware

As shown in the system overview(Figure4.1), airbags are inflated and deflated by the speaker's movements which are actuated by audio signals from PC. The actuation system is consists of a PC, an audio interface, an amplifier board set, and a speaker set, shown in Figure 4.2:

- PC. On the PC side, Max MSP was used to generate the required audio signals for push/pull movements of the speaker cone. By creating different audio patterns, we were able to render low frequency pressure and high frequency vibration.

- Audio Interface. A eight-channel USB audio interface (Roland - OCTA-CAPTURE) is used for separating audio channel.

- Amplifier Board Set. Pre-amplifier board which connecting with OCTA-CAPTURE receives audio signal from separated channel and delivers the single to power-amplifier board which output signals to speakers.

- Speaker Set. The full-range speakers(AURASOUND NSW2-326-8A[2]) were mounted on the closed air chamber where the air is transferred through a tiny nozzle where the audio signal is converted to a the air pressure. Each air bag is attached to a single speaker. When the speaker is actuated by an audio wave generated on the PC. The speaker generates the air pressure due to the continuous and rapid movement of the cone. This movement pushes and pulls the air in and out of the chamber, to inflate and deflate the airbag.

- Tube[3]. Transparent tube has a 1.8mm outer and 1.6mm inter diameter. It plugs into speaker cover and airbag to transmit air.

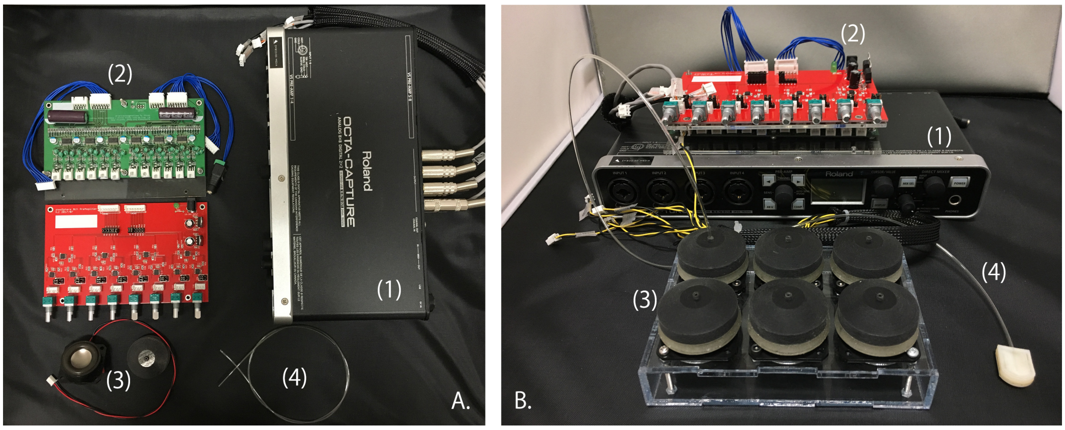

Figure 4.2: Hardware of the actuation system. (1)The audio interface. (2)The amplifier. (3)The speaker set. (4)The air tube.

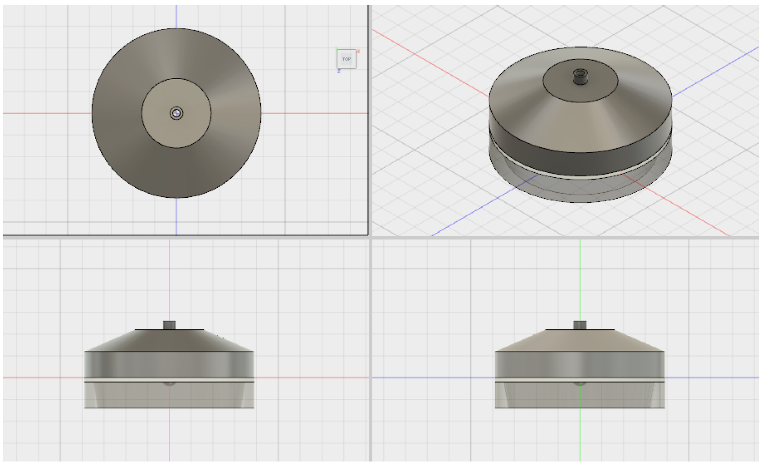

Figure 4.3: 3D model of speaker cover

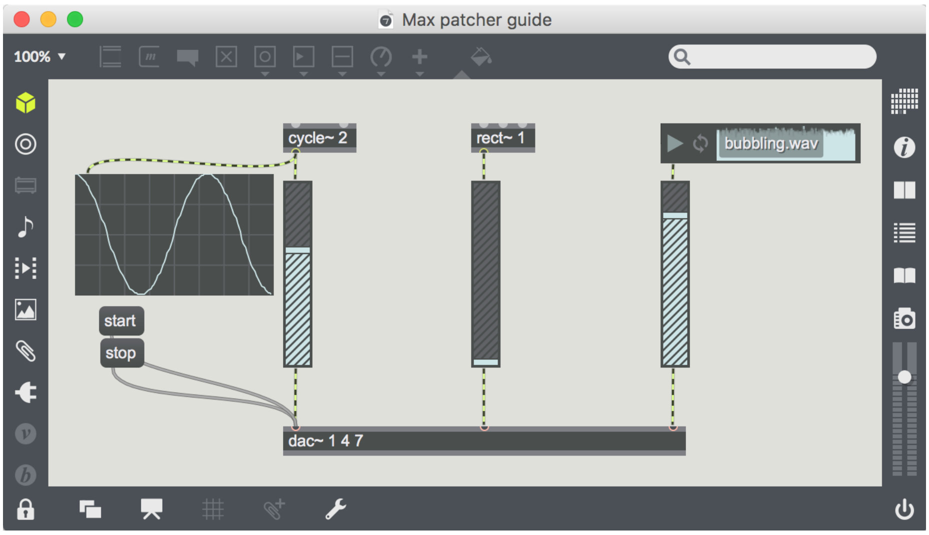

Figure 4.4: GUI of Max/MSP

4.2.2 Software

The audio signal generated from PC is programmed with MAX/MSP which is a visual programming language for music and multimedia developed and maintained by San Francisco-based software company Cycling '74. GUI of it is shown in Figure4.4.

The Max program is modular. Most routines exist as shared libraries. An application programming interface (API) allows third-party development of new routines (named external objects). The basic language of Max and its sibling programs is that of a data-flow system: Max programs (named patcher) are made by arranging and connecting building-blocks of objects within a patcher, or visual canvas. Objects pass messages from their outlets to the inlets of connected objects. Objects shown in in Figure4.4 is the commonly used objects in our actuation program. Object dac send audio signal to appointed channel. Object gain is a vertical bar to control volume. Object playlist can play sound files in .wav or .mp3 format. Object cycle generates a sinusoidal waves with a variable frequency set by the follow number. Before starting a patcher we should change the sound output device to OCTA-CAPTURE for transmitting audio signals to the speakers.

The sound resource of MAX/MSP could be sinusoids or captured/rendered texture based audio waveforms. If we play a sinusoid single, the haptic feedback has a obvious difference between high-frequency and low-frequency. The lower frequency bring the slower inflating speed which generates pressure. On the contrary, the higher frequency bring the faster inflating speed which generates vibration. Both low-frequency pressure and high-frequency vibration can be felt as a powerful tactile sensation. The nimble inflation/deflation time and continuous shift between inflation and deflation are advantages of the voice-coil actuation, that traditional air pumps can not do.

The actuation program renders tactile feedbacks through regulating the volumes and the contents of sound resources. There are two kind of rendering model for different haptic displays.

Texture rendering

The actuation system based on the voice-coil actuator supports a wide range of bandwidths, especially a full range speaker is used here. The mechanical vibration generated from sinusoidal signal can be used to simulate the roughness of objects. Replacing the sinusoidal signal with a recorded haptic textural sound file gives users more real textural feedbacks. The airbag acts as a non-mechanical vibrator and feel the tiny vibrations as it would felt on conventional tactile rendering systems such as TECHTILE-TOOLKIT [15] that uses voice coil vibrators.

Multi-dimentional force rendering

With a haptic display whose airbags are spatial-distributed, the multi-dimensional force rendering is available, that bases on both the interval time when inflating and deflating each airbags and the intensity of signals that used to actuate each airbags. For example, when we use a haptic display consists of 2 airbags, inflating the left airbag first then inflating the right airbag stronger can simulate a rightward force briefly. Similarly with three-dimensional force rendering. Of course, the interval time and intensity of signal effect the accuracy of the rendering.

4.3 Summary

A speaker-based actuation system is developed and trough practices in the implementation, we have known some features of the actuation system: 1) The speakers will going heat if low-frequency signal is send continuously. Once a speaker was broken while a 2Hz signal was keeps playing over 2 minutes. 2) A trick to reverse the direction of speaker-movements is exchanging the positive cable with the negative cable of the speaker. In common states, the positive cable of the speaker is connected to the positive port of the amplifier so the speaker-corn will going forward while playing a increasing clip of a waveform. But if we connect the positive cable of the speaker to the negative port of the amplifier, the speaker-corn will going backward while playing a increasing clip of a waveform. 3) Because the texture rendering based on the audio waveforms, for some haptic textures which are hard to be recorded we can create the waveforms artificially.

Notes

1 `https://www.roland.com/jp/products/octa-capture/features/`

2 `http://www.ari-web.com/aurasound/NSW2-326-8A/index.html`

3 `http://jp.misumi-ec.com/vona2/detail/110301969920/?ProductCode=MPUT1.8-10-C`

Chapter 5
Evaluation

In this chapter, we will describe the evaluation which has down from two aspects. From the technical aspect, the frequency characteristic was measured using a basic pattern airbag. From the psychophysical aspect, the accuracy of the multi-dimensional vibration rendering was evaluated. The power of haptic feedback is influent by size and thinness of airbags, so we try to characterize the relationship between power, frequency, size and thinness of a single airbag. Then according to the results, we will discuss the limitation of the system and the hidden effect of the evaluation.

5.1 Frequency Measurement

As a haptic display, the airbag should have a capability for providing user vibration or pressure. The inflation system described in the previous chapter is renders the sound signal in a full range. So could the airbag precisely presents the frequency generated by PC is a research question should be answered. The airbag used for evaluation is one of the basic pattern (Figure 3.4(b)) whose specification is $20mm \times 20mm \times 0.5mm(length \times width \times surfacethickness)$. Its bottom was fixed on a horizontal table plane, and we used an accelerometer ADXL345[1](max sampling rate: 3200hz) on its inflatabe surface. The accelerometer is attached to measure the vibration horizontal frequency and without any external force.

At first, Arduino Uno[2] is used to receive data from accelerometer through I2C protocol and outputs the data to a serial port. Then Processing[3] receives the data from the serial port and displays the data in a visualized graph for each axises. The programs we used are from a GitHub open source libraries[4] contributed by Bitflops. But a problem is the receiving rate of Arduino is too low to record the enough data. Even the sampling rate of accelerometer is up to 3200Hz, the data we actually recorded are only 80 per seconds. So we have to change the micro controller to a faster one. Finally, We used a NUCLEO-F767ZI[5] at a 2000Hz sampling rate to capture the data.

Ten sinewaves with the frequency of 2Hz, 10Hz, 50Hz, 100Hz, 300Hz, 500Hz, 800Hz, and 850Hz were presented as input signals for this evaluation. The volume of the amplifier was set to a quarter of the max volume. The result processed by Fast Fourier Transform(fft) are shown in Figure 5.1. We can see that frequency over 800Hz is presented on the airbag surface. Also 900Hz and 1000HZ sinusoids are send to airbag for a test. according to the results which are analyzed by fft, the output vibration can be detected by the accelerometer but its frequency was decreased. For example, we will get a output vibration with 760Hz frequency while we input a 900Hz sinusoids, and get a 660Hz vibration while the input is 1000Hz.

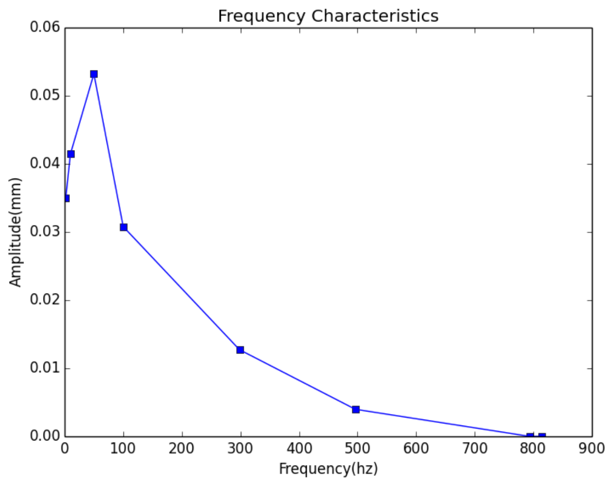

Figure 5.1: Frequency characteristics of the airbag surface.

5.2 Evaluate Multi-dimensional Force Rendering

This section for evaluating the accuracy of simulating a multi DoF haptic sensation. Both of abilities to rendering 2-DoF and 3-DoF tactile feedback have been evaluated. At first, experiments design will be described, then whole process to implement experiments will be introduced. Finally, data of experiment result will be analyzed.

5.2.1 Experiment Design

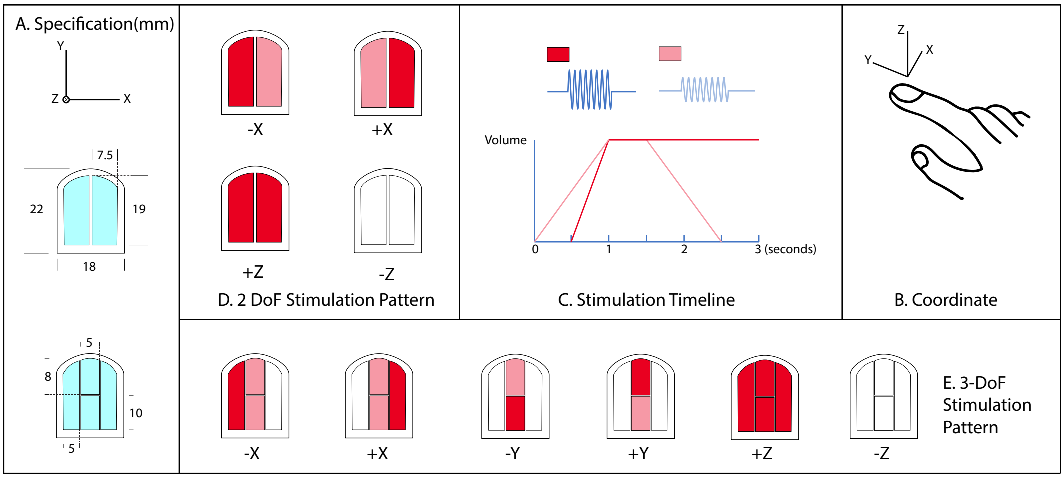

Figure 5.2: Experiment design for multi-dimension vibration rendering.(A. The specification of airbags what used for the experiment. B. The coordinate of fingertips. C. The stimulation given to participants each term. D. Four stimulation patterns for the 2-DoF experiment. E. Six stimulation patterns for the 3-DoF experiment.)

The purpose of this evaluation is for evaluating the accuracy of rendering the multi-dimension vibration patterns on a user's fingertip. Both the 2-DoF and 3-DoF tactile feedback have been evaluated. As shown in Figure 5.2, the experimental design is as follows:

Coordinates are defined as (B.) when referenced to the participants' fingertip, where the positive x-axis is towards the right of the fingertips, the positive y-axis is forwards with the fingertips, and the positive z-axis is towards the direction where vertical to the fingerpad.

Haptic displays employed in the experiment are characterized in (A.). One consists of two airbags to present the 2-DoF tactile sensation in the x and z axises. The other consists of four airbags to present the 3-DoF tactile sensation.

Signals for stimulation are two sinusoidal vibration with the frequency at 30Hz. Send each vibration to the different airbag in sequential manners can simulate multi-dimensional tactile feedbacks. One of them whose amplitude is half of the other is sent to the airbag earlier, according to the timeline which is shown in (C.).

Patterns of stimulation which represent to each directional information are shown in (D.) and (E.). There are four patterns for the 2-DoF experiment and six patterns for the 3-DoF experiment. The colors filled up airbags are matched with stimulation signals. White means non-forces rendered.

The relationships between directional information and stimulation pattern are listed in table5.1&5.2.

Table 5.1: Define coordinate in 2 DoF

+x	-x	+z	-z
Left to Right	Right to Left	Vertical Force on Fingerpad	No Force

Table 5.2: Define coordinate in 3 DoF

+x	-x	+y
Left to Right	Right to Left	Down to Up
-y	+z	-z
Up to Down	Vertical Force on Fingerpad	No Force

5.2.2 Experiment Implementation

We provided each pattern of stimulation randomly at 5 times for each participant for both 2-DoF and 3-Dof patterns. 10 participants (4 males and 6 females, ages between 24 and 28) took part in the experiment. The experimental tool for this test was programmed in MAX/MSP(figure5.3). The tool plays a stimulation randomly after its start button being pressed, and writes the pattern of the stimulation into a txt file. When a stimulation is finished, the participants will be reminded to select a pattern according to their intuitions.

During the experiment, participants are required to wear on a headphone where the white noise is playing to avoid the disruption. And only the start button and

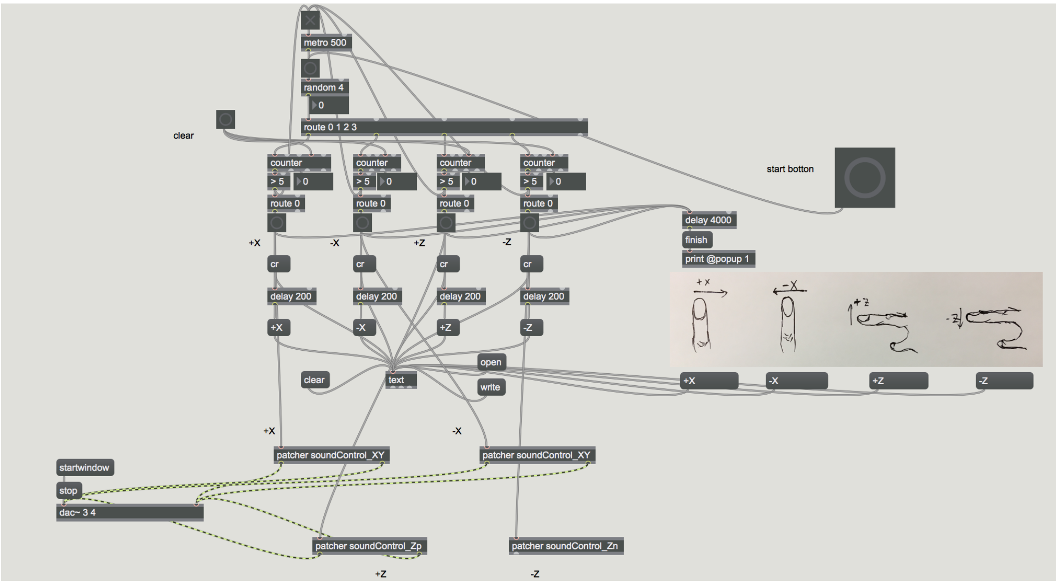

Figure 5.3: MAX Patcher for 2-DoF Experiment

selection button are shown to the participants in the GUI of the experimental tool. Figure 5.4 shows the scene of a participant doing the test.

5.2.3 Data Analyzing

The results of 2-DoF experiment is calculated as the confusion matrix shown in 5.5. And the results of 3-DoF experiment is calculated as the confusion matrix shown in 5.6. From the result of the 2-DoF test, we can see that the average accuracy is 84% and the negative X and positive Z have the highest mistook rates. A lot of participants confused with them. From the result of 3-DoF test, we can see that the average accuracy of distinguish 3-DoF directional information is 91% higher than 2-DoF sensation. -X and +Z still the directions that usually distinct by mistake.

The accuracy of negative z-axis which is 100% meaning the vibration is absolutely sensible. As observed, all the accuracies are over 76% and the max accuracy is up to 96%. The overall accuracy of the 3-DoF experiment is higher than the 2-DoF experiment, even the airbags used for it are smaller. This could be due to the design of the 2-DoF which has a larger contact surface with the finger-tip than the 3-DoF design. According to the feedbacks from participants, there are two participants have mentioned that they had clearly sensed the directions at

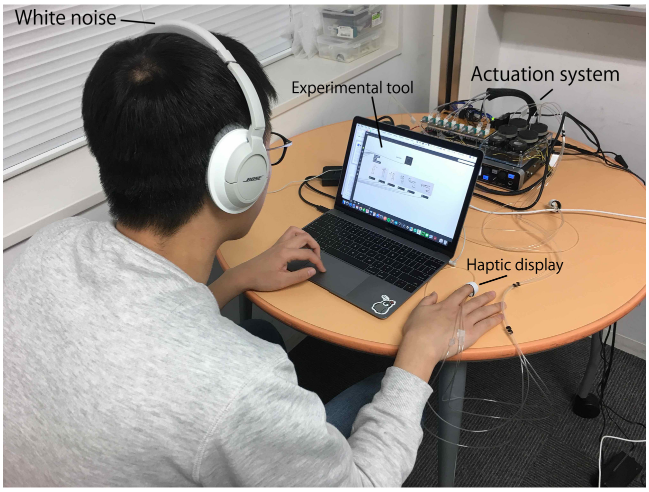

Figure 5.4: Participant doing test

Input pattern

Answer	-X	+X	-Z	+Z
-X	76%	8%	0%	8%
+X	10%	84%	0%	10%
-Z	0%	0%	100%	0%
+Z	14%	2%	0%	76%

Figure 5.5: Experiment results of 2-DoF

Input pattern-

Answer	-X	+X	-Y	+Y	-Z	+Z
-X	80%	2%	2%	0%	0%	2%
+X	8%	96%	0%	0%	0%	12%
-Y	8%	2%	94%	0%	0%	4%
+Y	2%	0%	2%	96%	0%	2%
-Z	0%	0%	0%	0%	100%	0%
+Z	0%	0%	0%	0%	0%	80%

Figure 5.6: Experiment results of 3-DoF

the beginning, but they had gradually become confused with the test going on. We identify that this reason of tiredness too may have contributed to the lower accuracies of the 2-DoF design.

5.3 Discussion

Through our evaluations we identified that the basic pattern of the airbag is capable of producing haptic frequencies upto 800Hz. In addition, we explored the capabilities of providing multidimentional vibration patterns with different designs of fingertip haptic airbags. However, we identify few limitations of this work.

As a starting point, these evaluation was limited to the 0.5mm thickness of the surface material and a few selected patterns for providing multi dimentional vibration patterns. With our future works we plan to expand these parameters to further understand the capabilities of this system.

Chapter 6
Application

In this chapter, two completed demonstration which apply our haptic display in two fields will be described. One applies the haptic display to directly touch with virtual objects in virtual reality. The other is used to transmit haptic collision data from telerobotic finger to operator's fingertip in a teleoperation system. Both of them are exhibited on the conferences or events, and received feedbacks from users who have experienced the demonstration.

6.1 Interaction in VR environment

Providing haptic feedbacks to user when the user interact with virtual objects is a tracking and actuating process that characterized as a framework in Figure6.1. There is a tracking device to track hands or other body parts which interacting with virtual objects. Collision vectors collected by the tracking device is translated to tactile data by tactile rendering algorithm. Then tactile data will be processed to actuating the haptic display.

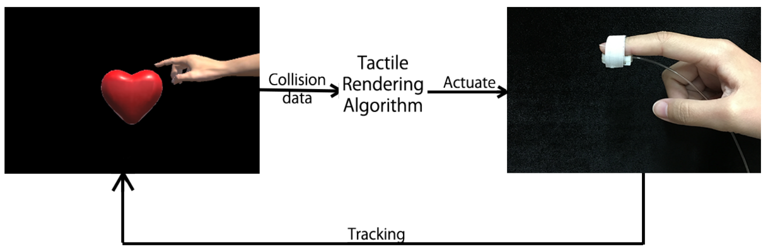

Figure 6.1: Tactile rendering framework

6.1.1 Demonstration Design

A demonstration that the user wore a haptic display to touch virtual objects is made. Figure6.2 shows its process. Unity 3D was used for creating a virtual reality environment where the user can touch virtual objects. Human hands will being tracked and simulated via Leap Motion[1]. Hand gestures and collision vectors are calculated by unity program, then judging whether tactile rendering commands should be send to the Max/MSP software via an TCP or UDP channel to trigger off actuations. The fingertip pattern haptic display consists of two airbags is used here and be worn on thumb and index finger. So 4 sound channels are used to output sound signal from MAX/MSP. In the Unity program, three virtual objects

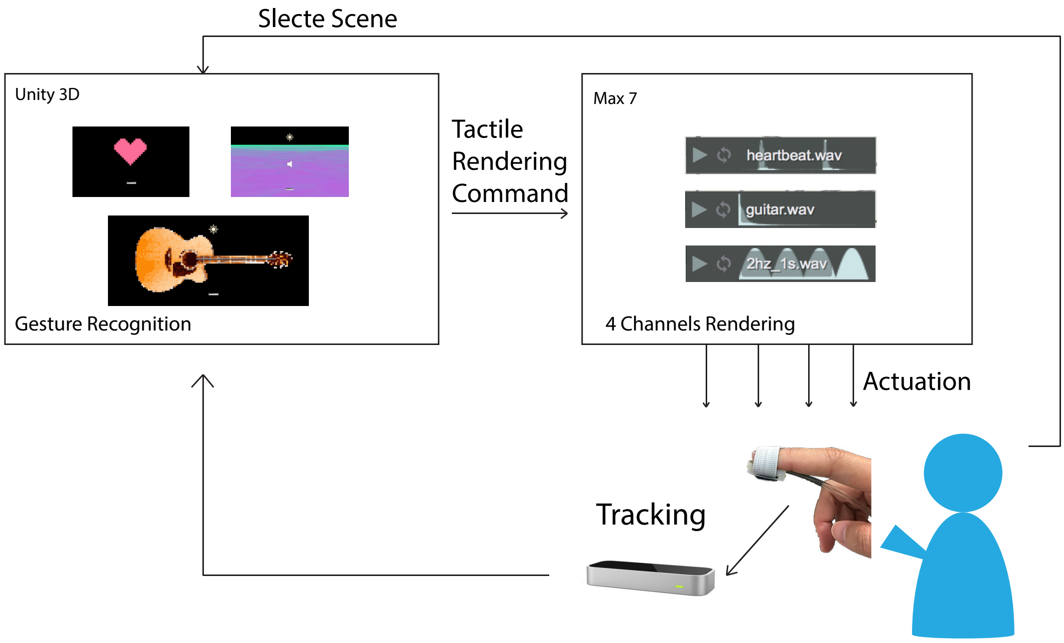

Figure 6.2: Block diagram of VR application

were created in the individual scene, they are a heart, a guitar and a billowing sea. Three kinds of haptic texture and visual graph are implemented for each object, user can press the key to switch into corresponding scene. Each scene will trigger off different sound file, the heart scene match to heartbeats sound, the guitar match to a string vibrating sound, and the sea match to 2Hz sound files which can simulate the waving feeling via play sound file to different channel asynchronously. Table6.1 match the input gestures with output haptic feedbacks.

In sense one for the virtual heart, heart will beating and a heartbeats sound

Table 6.1: Rendering Command

Scene	Gesture	Max Action	Output Channel
Heart	Catch	play	all
	Release	stop	all
Guitar	Index finger sloping to the left touch string	play	1
	Index finger sloping to the right touch string	play	2
	Index finger horizontal touch string	play	1,2
	Thumb finger sloping to the left touch string	play	3
	Thumb finger sloping to the right touch string	play	4
	Thumb finger horizontal touch string	play	3,4
Sea	Lay hand down	play	all
	Raise hand up	stop	all

file will playing for rendering heartbeats' tactile feedbacks when user catching or touching it. In sense two for the virtual guitar, a background guitar picture with one single playable strings constitutes the graphic user interface, when user play the string it will vibrating on both visual and haptic. If user plays the string with fingertip slopped to left and right, they will feel string vibration from left or right airbag. In the sense three for billowing sea, we control the interval time of inflating two airbags in 2Hz to simulate the feeling of lapping against with waves. When you put hand under water in virtual environment, you can feel the pressure shifting between two airbags.

underwater interaction

Can be used under water is a specific benefit of pneumatic haptic display because there is no electro-mechanical parts embedded. As shown in Figure6.3, a demonstration for underwater interaction is designed. Arduino with two wires is used as a water sensor for detecting whether airbag contacts water. One wire contacts airbag and the other sinks into the water, they are detecting data and transmitting it to Arduino through a circle. When the user wearing the haptic display that fingertip pattern contains single airbag and touching the water filled up tank, bubbling sound file that providing the use texture feedback will be played by PC.

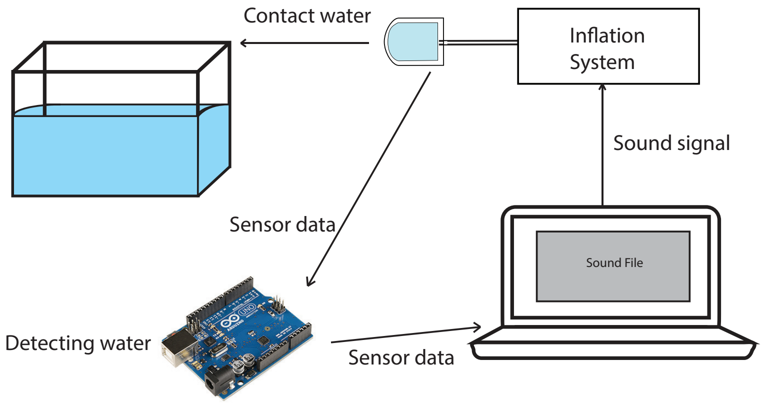

Figure 6.3: Process diagram of underwater interaction

6.1.2 Public Subjective Evaluation

This demonstration is firstly exhibited on SIGGRAPH 2017(Figure6.4&6.5), then exhibited on Embodied Media Open Lab, VRSJ2017, and KMD Forum2017. There are more than thousands people in a wide range of ages who have experienced the demonstration and given us lots of significant feedbacks. People who had not experienced haptic devices before often surprised by the vivid heartbeats feeling at first. People who had haptic experience before usually attracted by waving feeling and said that its a rare and extraordinary feeling. Majority of children who have experienced the demo are most excited when play guitar. Some words such as "It's so cool", "The feeling is so real", "Simple but effective" are received, and also some people suggest that it's good to apply to other filed except entertainment.

Fingertip pattern airbags have been changed once a day during exhibition, and no airbag have been broken. It proved the durability of the haptic display.

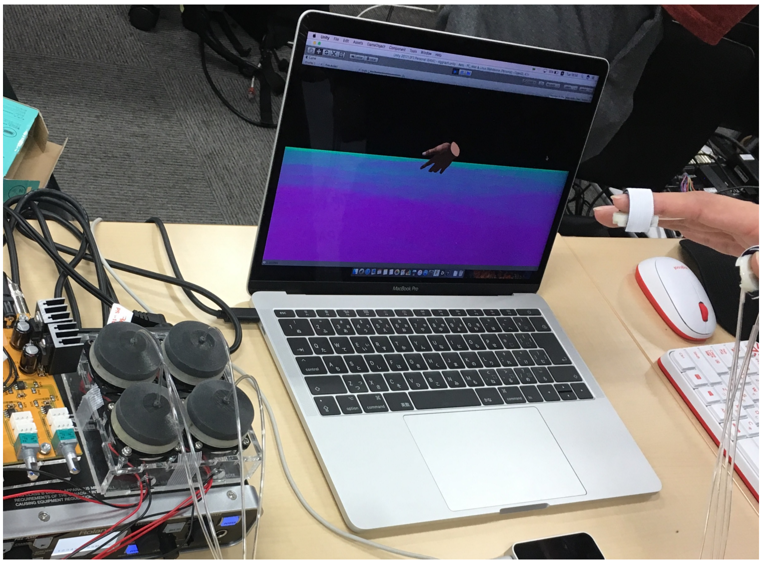

Figure 6.4: Demonstration of interacting with VR objects exhibited on the KMD Forum 2017

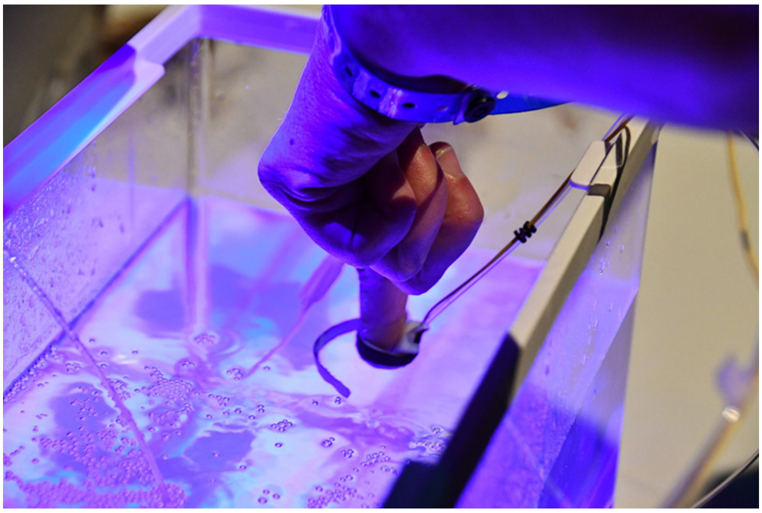

Figure 6.5: Underwater interaction exhibited in the Siggraph2017

6.2 Haptic Transmission

The transmission of haptic sensation is a technology that is able to enhance operator's experience in a teleoperation system. It allows operator to perceive remote objects instinctively via robotic hands. We apply our haptic display to a teleoperation system, to providing operator with haptic feedback which transmitted from a telecommuted robot.

6.2.1 Teleoperation System

Teleoperation system in technical environment is indicts a master-slave system that operator as a master remote control a robotic slave to interact with objects in slave's side. The slave could be a mechanical tool such as scalpel usually applied to medical field, also could be a robotic avatar which could work in the special environments human can't get in. Visual and audio information is transmitted to the operator from sensors which is mounted on slave, but it not enough for delicate operation without haptic sensation. So there are various haptic transmission systems that present tactile stimuli to the operator on the basis of the information sensed by tactile sensors have been developed.

6.2.2 Demonstration Design and Implementation

The NS Solutions Corporation(NSSOL)[2] is a company that has a teleoperated robot which can transmit visual and audio information to operator immediately through network. They want their system to support haptic feedback for enhancing operation experience. Because the robot is developed for industrial, it need a haptic display which can work in tough environments such as a factory. Our display is washable and waterproof to be used in the special environment. What's more, the 3D printed display part can be disassembled from the actuation system so even it is broken, it can be changed to a new one. The low-cost airbag can be regarded as disposable. Above advantages let NSSOL decide to combine our haptic display with their teleoperate robot and demonstrate the fruit on the NTT 5G Exhibition. The parts we shouldered is to receive the collision data which is sensed by touch sensors, then to render the tactile feedback to the haptic display. The force sensor used here is OPTOFORCE(Figure6.6). It detects force on it's spherical surface as a 3 dimensional vector. Fingertip pattern consists of two airbags haptic display is used here to provide 2 DoF feedback. To inflate left or right airbag is depends on which side of force sensor detects pressure. After receiving the vector data as x,y,z, we calculate the position and strength of force then mapping the data on a waveform which amplitude is 1, then send the waveform to related speaker for inflating related airbag. A dynamic waveform calculated with force data is sending to speaker during connection. If there is no force detected, the waveform will be a line which wouldn't trigger off speaker movements. Only when force detected, a fluctuating waveform will be calculated to move speaker.

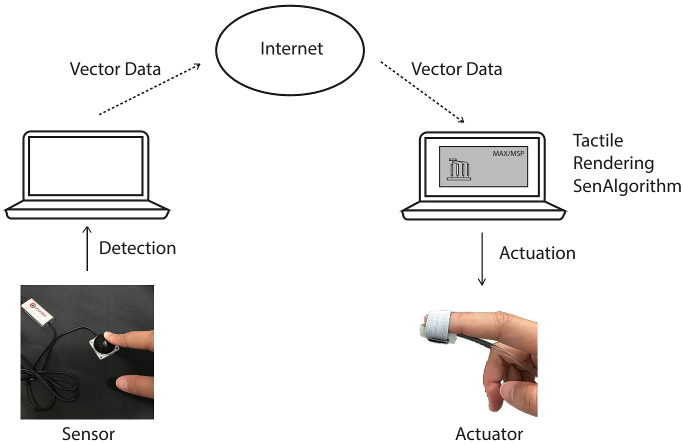

Figure 6.6: Process diagram of the haptic transmission

Figure 6.7: Demonstrating on the NTT 5G Exhibition.

In Figure6.7 is a photo showing the teleoperation system took on the 5G exhibition[3] held by NTT docomo. The miniature force sensor is attached on the robotic fingers and the haptic display is worn on the human fingers. For free moving, the speaker set is worn on the waist.

6.3 Discussion

From the demonstrations, we find advantages which is not aware of before. The durability of the airbag is over our expectation. Furthermore, because the airbag can be used under water, it is washable while got dirty. It the benefit let the airbag meet tough environments.

Also there is few limitation in practical applications. The airbags have to connect to an air tube which obstructs the users' motions. Moreover, the current hardware system of the actuation system is bulky and relatively heavy for mobile applications. However, the hardware used are for general purposes and can be further miniaturized for specific application purposes.

Notes

1 `https://www.leapmotion.com`

2 `http://www.nssol.nssmc.com`

3 `http://docomo-rd-openhouse.jp/mirai/index_mirai.html`

Chapter 7
Conclusions

We proposed a rapid fabrication method for creating pneumatic haptic displays which are based on the 3D printed airbag, and evaluated the ability of the haptic display to render tactile feedbacks in the thesis. Because of previous pneumatic haptic displays have a complex fabrication process, and previous 3D printed pneumatics have not focused on creating a haptic display. We trust a simple and rapid fabrication method to create customizable pneumatic haptic display is required. The fabrication process based on the 3D printing technology is friendly for beginner and contains all of the advantages of the 3D printing. And it is able to produce various haptic displays to meet different requirements. What's more, as the 3D printer becoming faster and more portable, anyone can get their own haptic display anytime and anywhere.

In this thesis, we introduced two wide backgrounds which are supported our research at first. That are the 3D print technology and haptic displays. Through discussing the possibility of fabricating a haptic display, our research purpose have been revealed. Then closely related works that including 3D printed works, pneumatic haptic displays and tactile rendering methods were described in details. Next, the design of the 3D printed airbag which is the basic element used to constitute haptic display was characterized. After that, the system we used for rendering tactile feedback to the airbag was explained. The ability of our system was evaluated in chapter 5, and two completed applications are described at last. Furthermore, the observation and limitation of this work is figured out in each discussion sections.

As the future work, we are able to fix the defects which are discovered in the experiments and demonstrations to improve the usability of the haptic display, such as adjust the softness or height of the fingertip-pattern display to attach finger pad closely. Furthermore, attaching airbag into the joints of 3D models will creating movements which perhaps can be used for making soft robotic toys. Also, we expect a new way to use the actuation system like playing vibration while the speaker-corn deviating from start plane.

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Related Publications

Feng, Y. L., Fernando, C. L., Rod, J., & Minamizawa, K. (2017, July). Submerged haptics: a 3-DOF fingertip haptic display using miniature 3D printed airbags. In ACM SIGGRAPH 2017 Emerging Technologies (p. 22). ACM.

Yuan-Ling Feng, Charith Lasantha Fernando, Kouta Minamizawa. AeroFinger: A 3-DOF Fingertip Haptic Display using Scalable and Miniature 3D Printed Airbags, World Haptics Demonstration. IEEE, 2017.