修 士 論 文 の 和 文 要 旨

研究科・専攻	大学院　情報システム学研究科 情報メディアシステム学専攻　博士前期課程		
氏　　　名	JEFFERSON PARDOMUAN	学籍番号	1250017
論 文 題 目	Design and Implementation of an Interactive Surface System with Controllable Shape and Softness 形状と硬度の対話的制御を可能とするインタラクティブサーフェスシステムの設計と実装		

要　　旨

「平面的で硬い」という従来のディスプレイの物理的制約は、ユーザが 3 次元的な形状を有するデータを扱う場合や触覚的な情報を有するデータと対話する場合に様々な制限を与えている．また，平面的なディスプレイ上で複雑な立体形状を閲覧・モデリングするためには，頻繁な視点移動や複雑な頂点操作等を伴う GUI 操作が必要である．

このような問題を解決するため，砂，粘土のような非平面的･柔軟な素材をサーフェスに取り入れて，従来のディスプレイにできない異なるインタラクションを可能にした研究が行われていたが，一つのデバイスで異なる物理性質を表現できるディスプレイはあまり研究されていない．

本研究は細かなパーティクルと気圧操作による硬さ制御技術に着目し，硬度可変ディスプレイの実装を行った．硬さ制御によって，軟らかいときに形状の変形や，用途に応じて形状を維持することもできる．

このディスプレイの可能性を探るため，硬さ制御を利用したモデリングアプリケーションを開発した．このアプリケーションでは，モデリング操作に応じて，適切な硬さを選択する事ができ，モデルが完成した時にディスプレイを硬化し形状を維持させることが可能である．

また，深度カメラを用いることで，タッチ入力による彩色が可能になり，作成したモデルをスキャンし，CAD データとして保存することもできる．さらに， 3D プリンターで出力することも可能にした．

このシステムは、従来のモデリング操作をより直感的する事ができるが，システム単独で形状を生成することができない．そこで，本研究では粒子運搬技術を用いて，ディスプレイの形状アクチュエーション手法も提案する．

この手法では，モデルの大まかな形状を生成することで，ユーザは形状の細部を自由にカスタマイズすることができる．この手法は，硬さ制御技術と同じくパーティクルと空気アクチュエーションを用いているため，低コストかつシンプルなシステムで実現することができる．

Master's Thesis (2013)

Design and Implementation of an Interactive Surface System with Controllable Shape and Softness

Graduate School of Information Systems
Department of Human Media Systems

Student Number : 1250017

Name : JEFFERSON PARDOMUAN

Main Supervisor : Professor HIDEKI KOIKE

Supervisor : Associate Professor TAKUYA NOJIMA

Supervisor : Professor SHUN'ICHI TANO

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Chapter 1

Introduction

1.1 Problem Definition

Rigid-planar physical limitations of conventional displays has brought many restrictions when the user handles or interacts with the data that has a three-dimensional shape or tactile information. For example, in order to view or edit three-dimensional shape on a planar display, complex GUI operations such as frequent viewpoint movement and/or vertex operations are required. Using a stereoscopic display, however, a three-dimensional image is displayed to the user but direct touch or physical contact with the displayed shape is not possible.

In order to address this problem, non-planar, deformable surface that allow the user to directly modify the data like modifying a physical object has been explored recently[11]. Vertagaal et. al refer these type of interface that "Uses a non-planar display as a primary means of output, as well as input. " and "Have the ability to become the data on display through deformation, either via manipulation or actuation." as an Organic User Interface(OUI) [37].

Flexible materials such as such as cloth [3], elastomer [31], sand and clay [27] has been utilized as display surface to provide a organic element with the surface input/output methods. These displays generally show the images on a tangible surface or convex shape, and the user can touch or deform this shape freely with his/her hands. However, the shapes that can be produced on the surface are limited due to flexibility limitations of the surface material. Similarly, physical parameters of the surface such as stiffness or smoothness can be changed only by modifying the underlying hardware configuration. Thus, interaction methods that the same system could provide to the user were limited.

In attempt to achieve surface with the ability to create and deform physical shapes, many researches have implemented and developed pin array display[13][17]. In this researces number of small pins mounted into actuators (motors, SMA, piston , etc) made it possible to change the display shape and height dynamically. Most of this researches also allow graphical projection haptic feedback to user hands input. Even though some of these researches has introduced a significance advancement in term of scalability and application. However, generally these type of shaped display still have limitation as follow:

- Type of shapes that can generated
  Most fundamentally they do not allow overhanged shape due to the pin array structure.

- Shapes height limitation
  Actuators have a limited linear range. If the shape formed by the interface exceeds this range, it will be clipped.

- Resolution of the actuated points
  Due to the size and complexity of the actuators, they cannot be packed densely enough to create a resolution capable of outputting a perceived continuous shape.

1.2 Research Objective

Our research goals is to realize the "ultimate" Organic User Interface(OUI) :

- Capable to visualize data both with graphical output and shape deformation

- Allow for user input through hand touch, gesture, deformation (either via manipulation or actuation) directly on the display output.

- Have ability to adapt and change both the shape and mechanical properties according to the contexts of use.

Considering both the current technology problem and these research goals, we define our research objective as follow:

1. Development and implementation of deformable surface with controllable softness properties, allowing for varied shape deformation (rough and detailed) and shape fixing.

2. Implementation of fool-proof application to explore the capabilities of the display with softness change included with graphical output and direct touch input.

3. Proposal of particles display shape actuation that compatible with the softness control properties.

1.3 Research Outline

In this research, we focused on the dynamic changing capability of display stiffness (softness) and developed novel shape changeable display that has high flexibility and supports variety of different interaction styles.

We propose "ClaytricSurface" an interactive surface with dynamically controllable softness. By enabling controllable stiffness, this surface can be functioned as both a traditional rigid planar surface and also a flexible shaped surface. Moreover, by changing the degree of surface softness, this surface also allows for the generation of various touch sensations as well as tactile feedback on direct touch input.

We demonstrate the usability and accessibility of our display by developing a 3D modeling application. Our system use touch input to control the softness so that the user can immediately feel the softness change while make adjustments on the fly. When the display at soft state user can significantly deformed the surface shape. At malleable clayley state, user can create more detailed shape. And when the display is stiff, display will maintain its shape despite of external force(touch input) added.

In this research, we also propose a new display actuation called "LivingClay" where surface volume and stiffness can be controlled using a single pneumatic conveying method. The display is able to function as both a flat rigid display surface as well as a variable height deformable surface.

In addition, we also proposed 2 type of actuator array configurations, allowing a slightly more complex shape generation. The first design is an improvement of the hClaytricSurfaceh allowing an automated shape reset and low resolution shape deformation. While, the second design proposed a low-cost, effective way to control an array of actuators using a multiplexed grid configuration.

Chapter 2

Research Background

Vertagaal et. al. define an Organic User Interface(OUI) characteristics as follow [37]:

1. Input Equals Output: Where the display is the input device.
   In future, when displays are curved, flexible or any other form, current point-and-click interfaces designed for fixed planar coordinate systems, and controlled via mouse etc. will not be adequate. Rather, input will depend on multi-touch gestures and 3D-surface deformations that are performed directly on and with the display surface itself.

2. Function Equals Form: Where the display can take on any shape.
   Today planar, rectangular displays, such as LCD panels, will eventually become secondary when any object, no matter how large, complex, dynamic or flexible will be wrapped with high resolution, full-color, interactive graphics. Therefore, designers need to tightly coordinate the physical shape of the display with the functionality that its graphics afford.

3. Form Follows Flow: Where displays can change their shape.
   When the display, or entire device, is able to dynamically reconfigure, move, or transform itself to reflect data in physical shapes, the 3D physical shape itself will be a form of display, and its kinetic motion will become an important variable in future interactions.

In this chapter we introduce a few works on Organic User Interface where the display has variable mechanical properties, shape changing ability, or both.

2.1 Display with Variable Mechanical Properties

Here we introduce few projects that investigate computationally controlled material properties, such as viscosity, magnetical attraction-repellence, and stiffness.

2.1.1 Controllable Viscosity

Viscosity is resistance of a fluid to a change in shape, or movement of neighbouring portions relative to one another.

MudPad

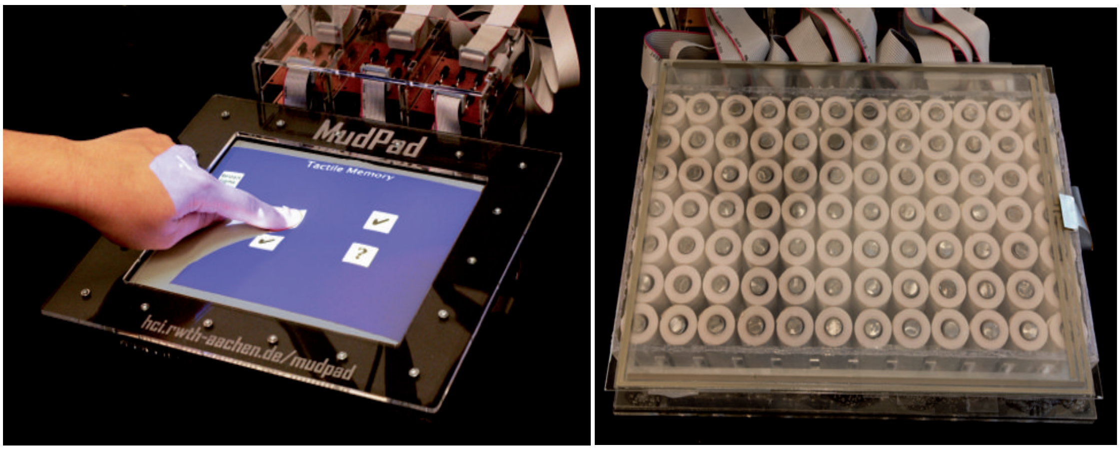

Figure 2.1: Mudpad system

MudPad [14], is a system that capable of localized active haptic feedback on multi-touch surfaces. An array of electromagnets locally actuates a tablet-sized overlay containing magnetorheological (MR) fluid. MR fluid is a smart fluid whose viscosity can be altered linearly by applying a magnetic field of variable strength. Viscosity levels range from fluid like water to viscous like peanut butter.

The reaction time of the fluid is fast enough for real time feedback ranging from static levels of surface softness to a broad set of dynamically changeable textures. As each area can be addressed individually, the entire visual interface can be enriched with a multi-touch haptic layer that conveys semantic information as the appropriate counterpart to multi-touch input. The usage scenarios of this surfaces including virtual keyboard, music squencer, and secure touchpad input.

HapticCanvas

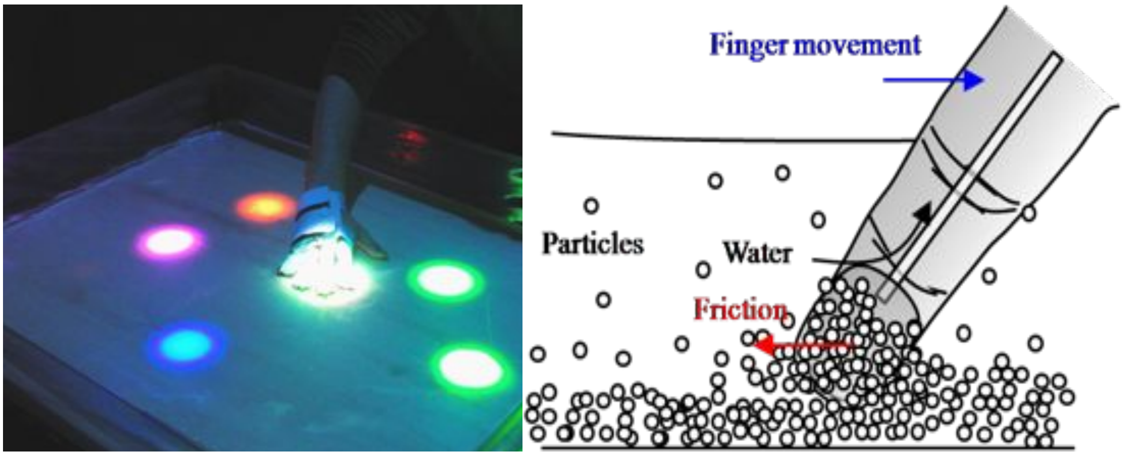

Figure 2.2: HapticCanvas system

Other research that focuses on providing dynamic viscosity control is HapticCanvas[40]. HapticCanvas utilizes dilatant fluid under the water to provide the users fingers with variable fluid resistant. Dilatant fluid is slurry made from water and starch which is the change in the external force influence the state from liquid-like to solid-like properties. If the user put their hand into the dilatant fluid, the device(sucking tube with the filter) equipped on the users fingertips vacuum up the water, changing the viscosity state of the dilatant fluid.

2.1.2 Controllable Magnetic Attraction and Repellence

FingerFlux

FingerFlux[38] is an output technique to generate near-surface haptic feedback on interactive tabletops. This system combines electromagnetic actuation with permanent magnets attached to the user hand. FingerFlux lets users feel the interface before touching, and can create both attracting and repelling forces. This enables applications such as reducing drifting, adding physical constraints to virtual controls, and guiding the user without visual output. The users can feel vibration

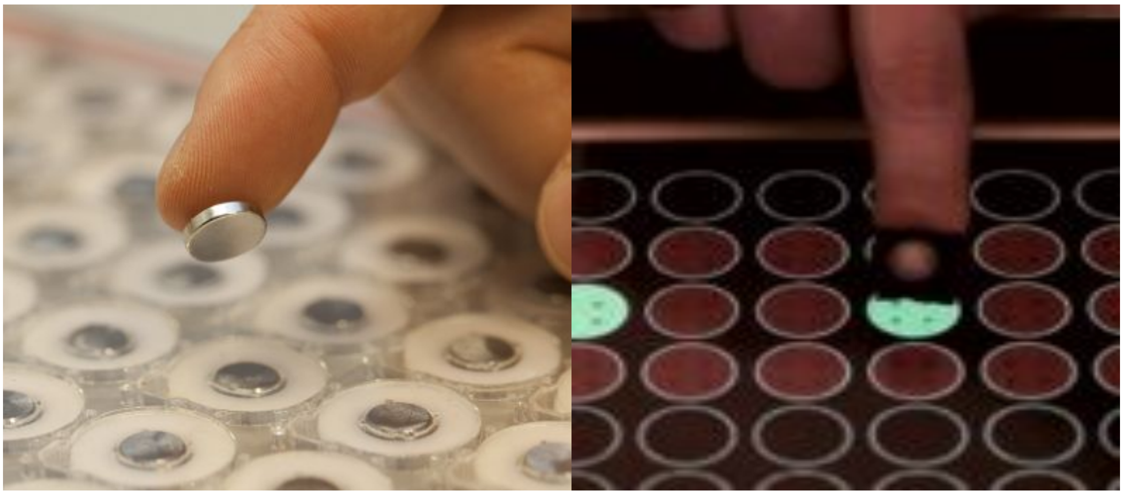

Figure 2.3: FingerFlux system

patterns up to 35 mm above the table, and that FingerFlux can significantly reduce drifting when operating on-screen buttons without looking.

Magnetosphere

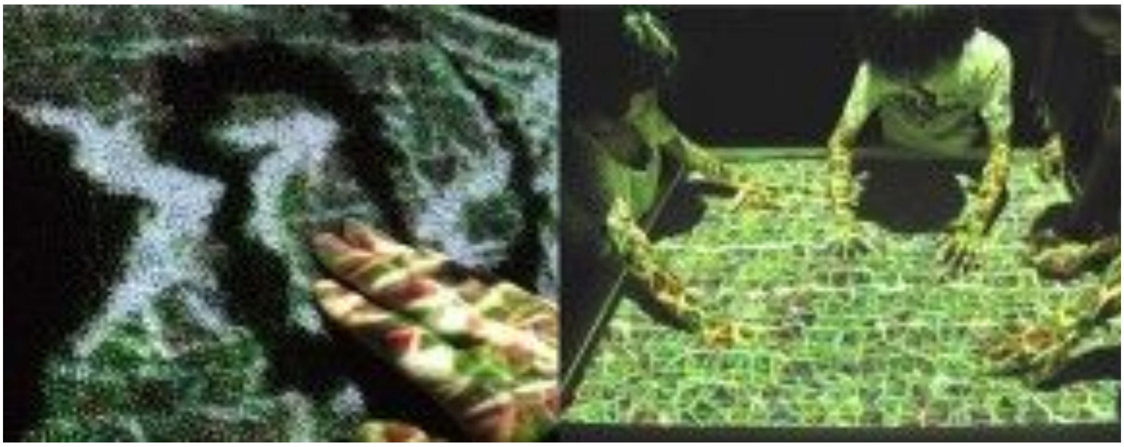

Figure 2.4: Magnetosphere system

Magnetosphere[16] is an interactive work of art that provides novel tactile sensations by changing the display texture. It utilizes small (1.2mm diameter) steel balls as a projection screen and array of the electromagnetic magnets placed under the table. The texture is changed by controlling magnetic attraction between electromagnets and steel balls partially. The aim of this development is to experiment with the depiction of video images together with actual tactile sensations.

2.1.3 Controllable Stiffness

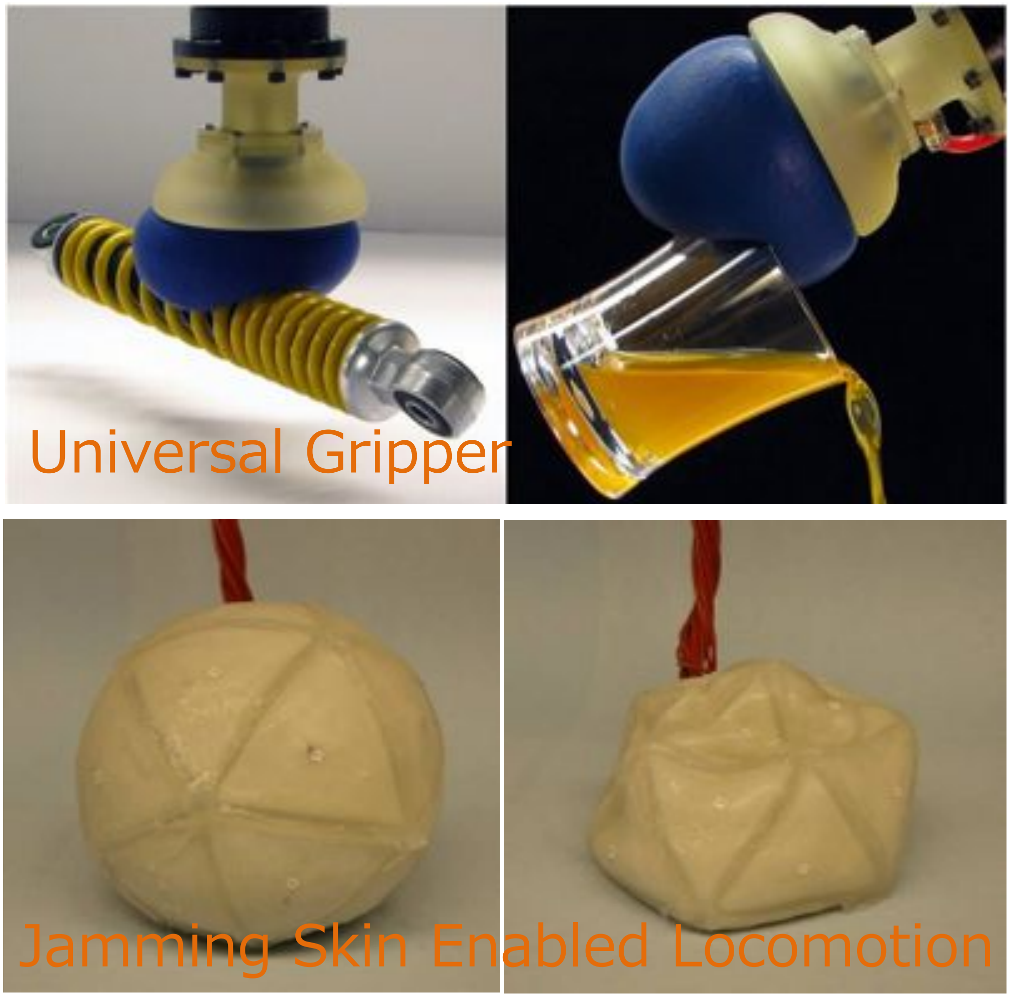

Figure 2.5: Upper: Universal Robot Gripper, Bottom: JSEL system

Stiffness control using vacuum jamming technique (ability to switch granular material state between soft and rigid) has been applied in various areas due to the capability of changing/fixing shape and rigidity controlled by only air pressure. E.g. for packing of coffee, pressure gypsum for firefighters or a fingerless robot arm that can grasp various objects without requiring complex mechanical structure[1], and as movement actuation of soft flexible ball shaped robot[34].

ClaytricSurface

Our research earlier works by Sato et. al[20] have presented the capability jamming technique for interactive surfaces and demonstrating prototypes at several international conferences. They developed an interactive interface for entertainment use, allowing the user to experience the possibilities of variable stiffness display. They first proposed the basic concept and implemented a prototype system at ACM ITS2011 and ACM SIGGRAPH2012 with a shape modeling application.

Jamming User Interface

Figure 2.6: Jamming User Interface system

Follmer et al.[4] discussed potential applications of the adopted jamming technique in the HCI field and presented different types of application examples including future mobile devices, physical input devices or interactive surfaces. They proposed, in particular, the use of capacitive shape sensing and rear-projection techniques.

2.2 Display with Controllable Geometry

Shape displays are haptic interfaces with the ability to create and deform physical shapes in real time. The idea of computationally controlled matter to create an immersive visual and haptic sensation was first described by Sutherland in 1965 as the ultimate display[35]. Most shape displays are not only output devices, but also allow user input. The approach of interacting with computers through physical embodiments of information is similar to the concept of Tangible User Interfaces (TUI) introduced by Ishii et al.[12].

2.2.1 Pin Array

Pin array display has been a popular method to generate 2.5D geometry on shaped display. The surface display created by Hirota and Hirose in 1993 [9] consists of a 4 x 4 linear actuator array. The actuators form a physical surface from the depth buffer of arbitrary 3D geometry.

Iwata et al. developed FEELEX in 1995 to overcome short-comings they identified in their previously constructed haptic interfaces tethered to the human body [13]. FEELEX consists of a malleable surface deformed by an array of 6 x 6 linear actuators. A top-down projector is used to create visual feedback on the surface. Through embedded pressure sensors the system reacts to the users push. An example application renders a moving creature reacting to touch input of a single user. A second version, FEELEX 2 decreases the spacing between the actuators for use as a medical palpation simulation device. While FEELEX displays are able to sense user input through touch, they do not allow additional input techniques.

Digital Clay is a research initiative at Georgia Tech investigating various shape rendering devices and their application as human computer interfaces. One of the

Name	Actuation method	Number of actuator	Display size	Maximum height
FEELEX	Motor driven screws	6 x 6	240 x 240 mm	8 cm
FEELEX 2	Piston crank mechanism	23	50 x 50 mm	1.8 cm
Lumen	Nitinol actuator (SMA)	13 x 13	84 x 84 mm	6 mm
Digital Clay	Hydraulic	5 x 5	25 x 25 mm	48 mm
Surface display	Slider crank mechanism	4 x 4	120 x 120 mm	5 cm
XenoVision Mark III	Electric	7000	91 x 122 cm	15 cm
Relief	Belt actuation	12 x 12	45 x 45 cm	13 cm
inForm	motorized slide potentiometer	30 x 30	381 × 381 mm	100 mm

Table 2.1: Comparison of pin array display

proposed mechanisms is a 2.5D shape display [29], with applications proposed for 3D modeling by sculpting with fingers. A functional prototype with a 5 x 5 array of hydraulically driven actuators was developed. The proposed interactions are not evaluated on an actual 2.5D shape display, as they would require resolution and sensing capabilities that have not yet been achieved.

Lumen by Poupyrev et al. [28] is a shape rendering apparatus driven by a 13 x 13 nitinol actuator array, similar to the apparatus of Pop-Up [23] . Graphic overlay is integrated into the device by lighting each actuated pin with a monochrome LED. Applications for Lumen include animated shapes, reconfigurable tangible user interface elements, and connected shapes for remote presence. The input mode is similar to that of a touch screen with tactile feedback, thus it does not explore additional interactions, beyond direct touch.

The XenoVision Mark III Dynamic Sand Table trades out- put speed for a simplified actuation mechanism, which enables a high resolution through 7000 actuators [26] . As rendering a complete shape on the current system takes more

Figure 2.7: Pin Array display

than 30 seconds, users cannot interact with the physical shape in real-time.

Gemotion Screen by Niiyama and Kawaguchi [24] utilizes pneumatically actuated flexible fabric screens with front projected graphics to display organic art.

Glowbits[10] by Daniel Hirschmann is a 2D array of rods with attached LEDs; the motorized rods can move up and down and LEDs can change their colors.

Photonastic Surface by Oguchi et al. proposes a novel mechanism to address individual actuators of 2.5D shape displays using projected light [25] .

Relief, developed by Leithinger and Ishii [17] proposes an actuator apparatus based on commercial hardware and open-source components for low cost and scalability.

InForm, by Folmer et al. explore the utilization of shape displays in three different ways to mediate interaction: to facilitate by providing dynamic physical affordances through shape change, to restrict by guiding users with dynamic physical constraints, and to manipulate by actuating physical objects[5].

On a significantly larger scale Aegis Hyposurface[22] is a wall-sized structure constructed out of interconnected metallic plates actuated by an array of pneumatic pistons. The surface of the wall can dynamically change its shape, either autonomously or in response to external events such as human movement captured by a camera. Images can be projected onto the surface. The Aegis Hyposurface is an example of an actuated device on the scale of a building. Direct haptic interaction with such devices is not possible and they are difficult to use at home.

2.2.2 Magnet

ForceForm

ForceForm [36] by Jessica et. al use an array of electromagnets and a deformable membrane with permanent magnets attached to produce a deformable interactive surface. ForceForm supports user input by physically deforming the surface according to the users touch and can visualize data gathered from other sources as a deformed plane. They explore this interface for usage scenarios such as: on screen

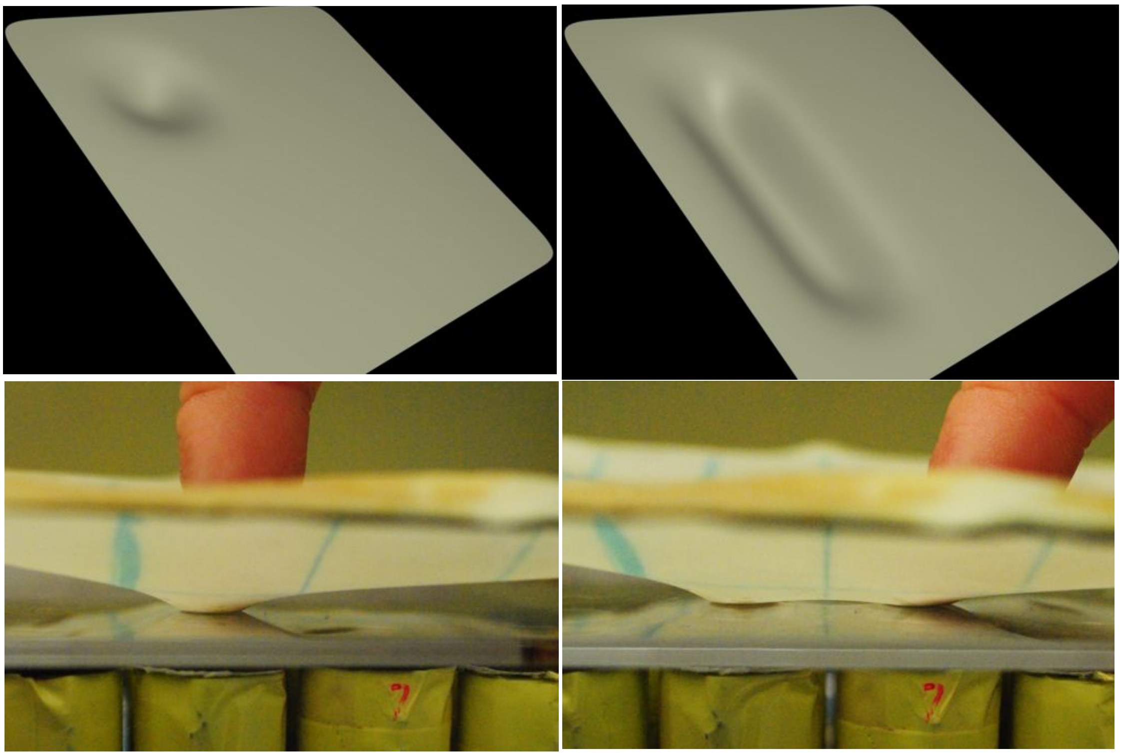

Figure 2.8: HapticCanvas System

keyboard and terrain modeling. They also outlined the performance of the system, including original method to increase electromagnets power without extra energy consumption.

2.2.3 Ferromagnetic Liquid

Another example of shape display is the art installation Protrude, Flow by Kodama and Takeno [15] . In that installation ferromagnetic liquid was actuated by an array of magnets to dynamically create a variety of beautiful, organic-looking shapes (Figure 2.9 left). Similarly, the Snoil device by Martin Frey[6] , uses an array of magnets located under the magnetic fluid to create arbitrary low-resolution bitmap images(Figure 2.9 left). Although both devices are very interesting and impressive, direct interaction with them is difficult: we cannot expect people to touch the magnetic fluid with their hands.

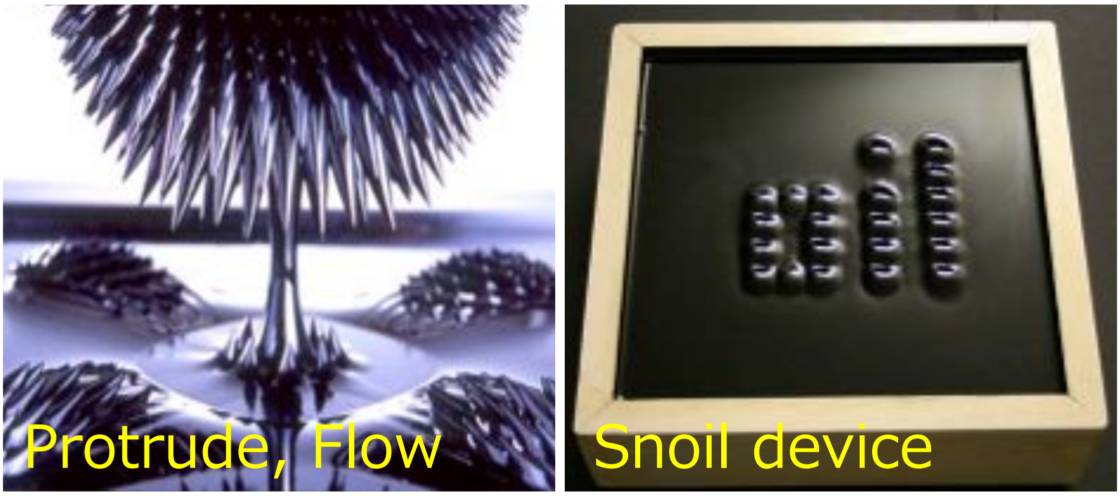

Figure 2.9: Left: Protrude Flow, Right: Snail

2.2.4 Pneumatic Actuator

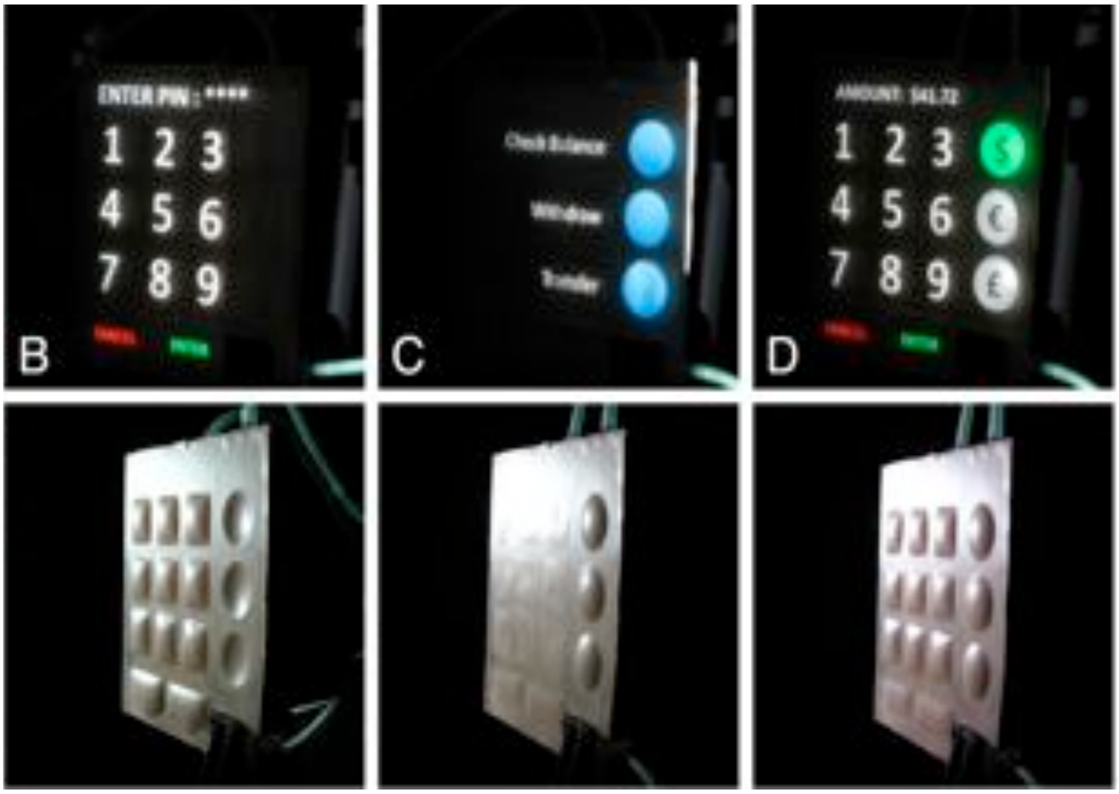

Figure 2.10: Dynamic Changeable Button system

Harrison et. al. [8] developed button overlays that consisted of inflatable buttons, with rear-projection multi-touch display. This device allow display surface buttons that can be positively or negatively inflated for tactile feedback. However, the buttons cannot be altered once the overlay has been made. Additionally, each button requires a pneumatic control to be able to operate independently.

2.2.5 Vacuum Jamming Method

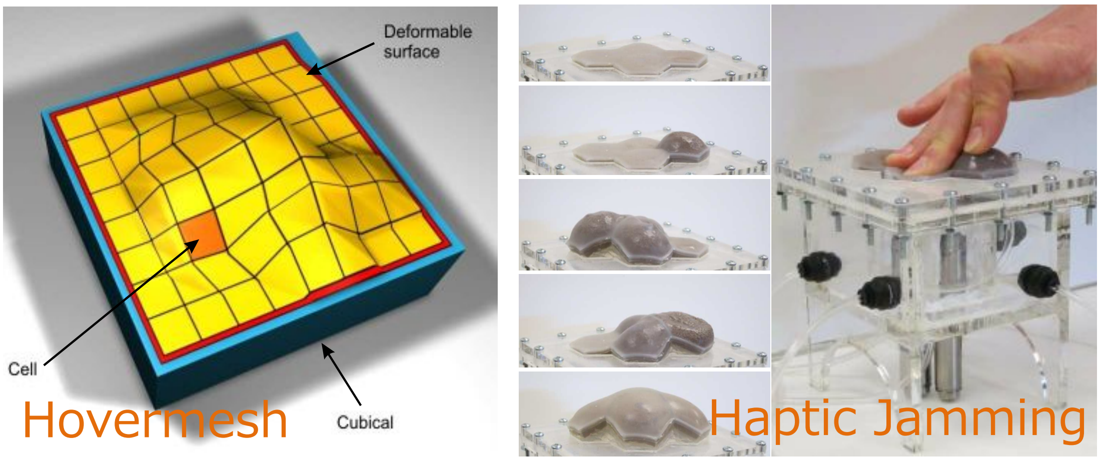

Figure 2.11: Left: HoverMesh system, Right: Haptic Jamming system

HoverMesh[21] implements a jamming-like stiffness control in an attempt to achieve a self-deforming tangible user interface. It consists of an array of mesh that has selectively controlled stiffness. The mesh can transform into different shapes through pressure controlled air chambers and the surface mesh solidifies given the state of the air chambers. This research suggested a new techniques for jamming-inspired surface mesh deformation.

Haptic Jamming implements both shape deformation and variable stiffness properties for a device using a combination of particle jamming methods with pneumatic actuation[33]. Similar to HoverMesh, the shape deformation is achieved by controlling the pressure of the air chamber and pneumatic actuators inside the display to solidify each mesh respectively. They also conducted an evaluation of the obtainable geometry shapes with this method.

2.3 Summary

Organic User Interfaces (OUIs) embrace the advances of new technology and materials to enable deformable and actuated interfaces of arbitrary shapes. Major enabling technologies for such interfaces have included advances in sensing, display technology[27] and mechanical actuation[13], but few projects investigate computationally controlled material properties, such as stiffness.

Recently, the potential of jamming to control material stiffness has been explored in various engineering fields such as robotic [1][34], deformable Interface[4] and shaped display [21][33]. However, most of these work only utilized the jamming to instantly stiffening granular material without exploring the jamming ability to exhibit a various state of softness. We, on the other hand, explored the possibility of modeling tools with capability to change the softness by utilizing vacuum jamming method.

Lot of research has implemented actuated pin array structure to allow shape deformation. These research, however, still have a lot of limitation such as shape resolution and overhanged shape expression. In this research, we introduce a particles based deformable display, allows for detailed shape deformation while allowing easy massive deformation and shape fixing by changing display softness respectively. In addition, we also introduce a new type of shape actuation method that has high compatibility with vacuum jamming method.

HoverMesh and Hapting Jamming also introduced a combination of vacuum jamming with mechanical actuation (pneumatic and cylinder piston) to allow both shape deformation and stiffness control. These researches, however, still have some limitation such as: complex system, resolution degradation, and compatibility with vacuum jamming. In this research, we developed a particles volume change actuation using pneumatic conveying method. This technique allow for both stiffness control and shape actuation with one closed simple system and ability to maintain the shape while changing the softness.

2.4 Research Positioning

We define our contribution in this research as follow:

1. Implementation of variable stiffness display with a high range and detailed softness variation using vacuum jamming technique.
2. Evaluation of pressure vs stiffness relation.
3. Implementation of depth camera based touch detection, that allow dynamic surface deformation.
4. Evaluation of depth camera based touch detection on flat-rigid, flat-soft, convex and concave display.
5. Development of modeling application that allow stiffness change corresponding the modeling work.
6. Proposal of new display shape actuation that allow both volume change using pneumatic conveying method, as well as stiffness control.
7. Design of array actuator system allows for complex shape deformation and low-cost scalable control system.

Chapter 3

Stiffness Control Propossal

With deformable displays, surface stiffness is a significant parameter to be considered. For example, soft surface is deformable and have a high flexibility. On the other hand, rigid surface is stiff and resistant to deformation from external forces such as gravity, or direct user touch. Furthermore malleable surface such as clay has a reversible shape deformation and preserve the shape against weak external force (gravity).

Though surface stiffness has a great influence to the possible interaction and shape representation of deformable surface, however, until recent years this stiffness parameter has been regarded as a material-dependent, static parameter. In this research, we focused on the jamming techniques[19] to control the surface stiffness.

3.1 Stiffness control theory

Jamming is the mechanism by which particulate material can transition between a liquid-like and a solid-like state. The most commonly experienced form of jamming can be achieved by raising the density of granular material through confining and reduce the container volume. However, in systems comprised of more microscopic constituents, such as colloids or molecular liquids, temperature is another relevant control parameter and jamming coincides with the temperature-dependent glass transition. Furthermore, jamming and unjamming can be driven by applied stresses, such as shear. The phase diagram introduced by Nagel and Liu (Figure 3.1)[19] shows how jamming in its most general form is controlled by three key parameters: the degree of geometrical confinement (given by the particle packing density), the temperature, and the applied stress.

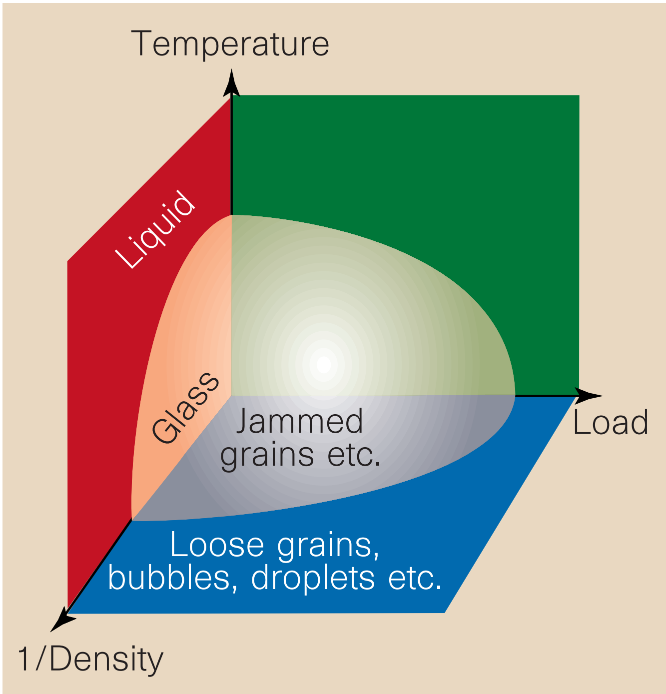

Figure 3.1: Possible phase diagram for jamming particles

In this research, the focus will be on jamming occurring due to a pressure differential or can be called vacuum jamming[34]. Vacuum jamming is commonly experienced in products such as vacuum packed coffee which is shipped in a stiff (solid-like) brick(Figure 3.2). When this brick is punctured, releasing the confining vacuum, the coffee particles behave liquid-like. Though jamming itself can do no net external work on the environment to enable mobility, it can be used to modulate the work performed by another actuator.

For instance, consider the simple case of confined small light particles such as sand inside a flexible container. At atmospheric pressure, it shows a smooth liquid-like properties due to the particles flow freely inside the container (figure3.3 left) . However, if the air between the particles is reduced (decompressed). Pressure different with ambient air apply stress into the container, condensing the partincles density and raising the frictional forces between the particle grain. At this state,

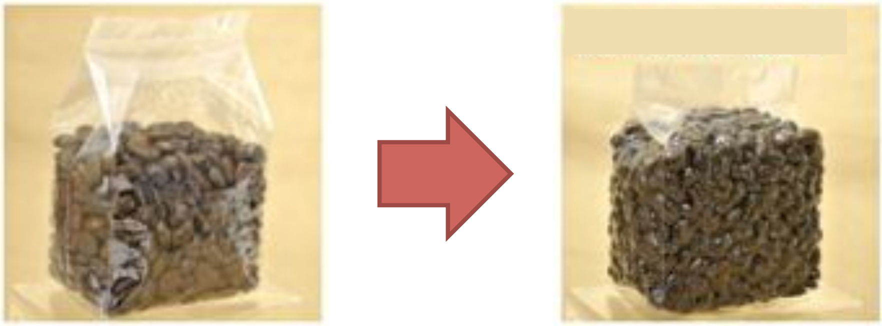

Figure 3.2: Coffe vacuum pack

the surface show a clay-like mellaeble property (figure3.3 midlle). Finally, when the pressure decreased any further, the particle density will excess the material thresshold, resulting the particles interlocked as one rigid object(figure3.3 right). At this state, the surface exhibit a stiff properties maintain the shape againts external force. The surface can then be unjammed by increasing the internal pressure, releasing the particles from external stress.

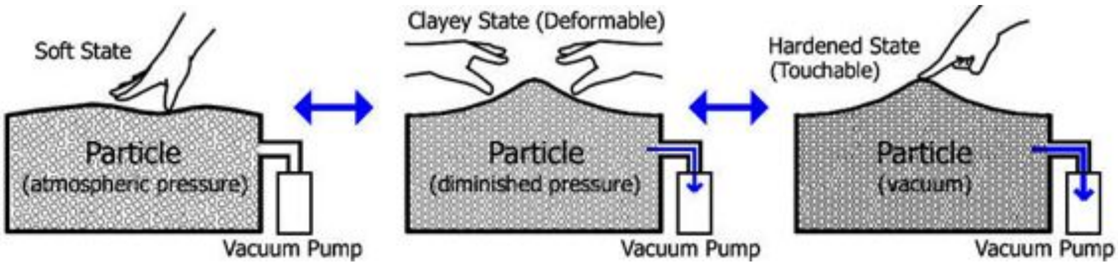

Figure 3.3: Vacuum jamming based stiffness control

3.2 particle material selection

Basically, all granular material exhibits the phenomenon of vacuum jamming. However, the strength of the effect can vary based on the size, shape, and compressibility of the particles. Fig. 3.4 shows the effective flexural modulus vs. vacuum level for several commonly available particulate materials[34]. (Flexural modulus is the flexural strength of a material to resist deformation under load). This figure show us how the flexural modulus increase along with the vacuum level. This figure also show that the change in flexural modulus is different depent on the particle material, size, shape, etc.

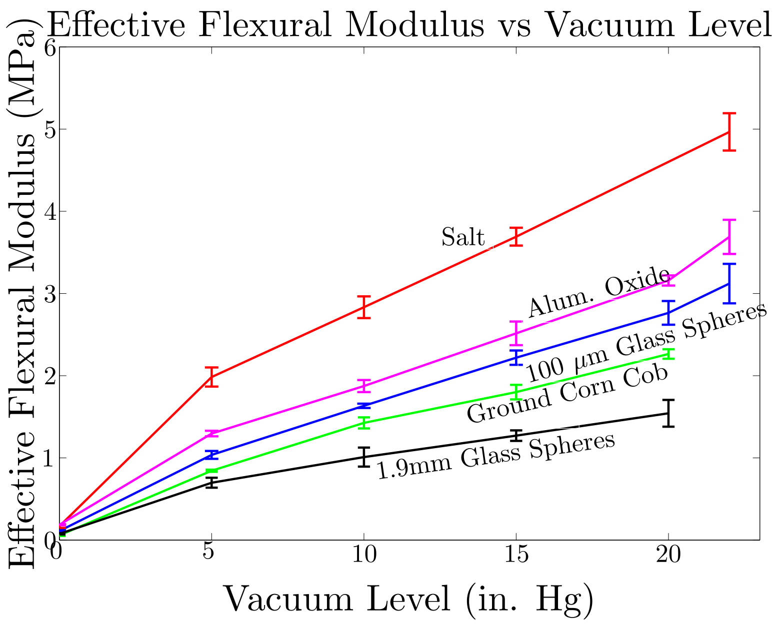

Figure 3.4: Effective modulus vs Vacuum Level for various granular material

Material	Average Diameter	Shape
Large Glass Spheres[1]	1.9mm	spherical
Fine Glass Spheres[1]	100μm	spherical
Aluminum Oxide[2]	100μm	rough and angular
Table Salt[3]	0.3mm	cubic
Ground Corn Cob[4]	0.8mm	rough and angular

Table 3.1: Granular materials physical characteristics

Overall, salt particle has the biggest flexural modulus change (due to the small size and cubical shape) and the 1.9mm glass sphere has the lowest change (due to the big size and spherical shape). However, maximum flexural modulus is not the only variable of interest in designing a surface with controllable softness.

Also Important factor to determine the expresiveness and usability of the surface interest is how liquid-like or how smooth the particle flow in its unjammed state. We found this characteristic of granural material is expressed in the angle of repose (angle of repose is the maximum angle to the horizontal at which granural particles will remain without sliding). Table 3.2 show the average angle of repose for the five materials that were measured in flexural modulus[34]. From this table, in contrast with the flexural modulus result, the 1.9mm glass spheres has the most liquid-like properties(21.4°). Meanwhile, the ground corn cob and table salt is the least in term of liquid-like properties.

Material	Angle of Repose(^{o})
1.9mm Glass Spheres	21.4
100μm Glass Spheres	26.6
Aluminum Oxide	35.9
Table Salt	37
Ground Corn Cob	40

Table 3.2: Angle of Repose Table

By comparing both the flexural modulus and Angle of Repose of several granular materials, we can conclude that particle choice is an important factor to determine :

1. The expressiveness of the shape
   Smaller particles have bigger flexural modulus change, making it able to exhibit a wide range of stiffness level. One of our display requirement is the ability to be hardened high enough to exhibit rigid object, therefore a small particle is better.

2. The usability of display
   Smoother, rounder, and lighter particles have greater angle of repose value, indicating the capability to exhibit a liquid-like softness. One of our research requirement is an easy to use, therefore it required to be as soft as possible.

3. Application

One of our research objective is to create a modeling application with softness change capability.

Considering the above factor, in this research we selected 1mm diameter polysteryne particles as particles material, because of it's light-weight, smooth properties, round shape and small size. One of our consideration is, this polysteryne particles materials have Angle of Repose of 21.4° [18].

3.3 Pressure vs softness experiment

In this study, we conducted an experiment to investigate the relationship between pressure inside the display and the change surface softness when using 1mm polystyrene beads as particle material.

In this experiment, pressure was changed gradually from vacuum (maximum vacuum reached was -18kPa) to atmospheric pressure levels. At each step, constant force that simulates touch contact of user finger is applied into surface and the displacement is measured. (This displacement value is parameter that represent the softness state of the surface at each vacuum level).

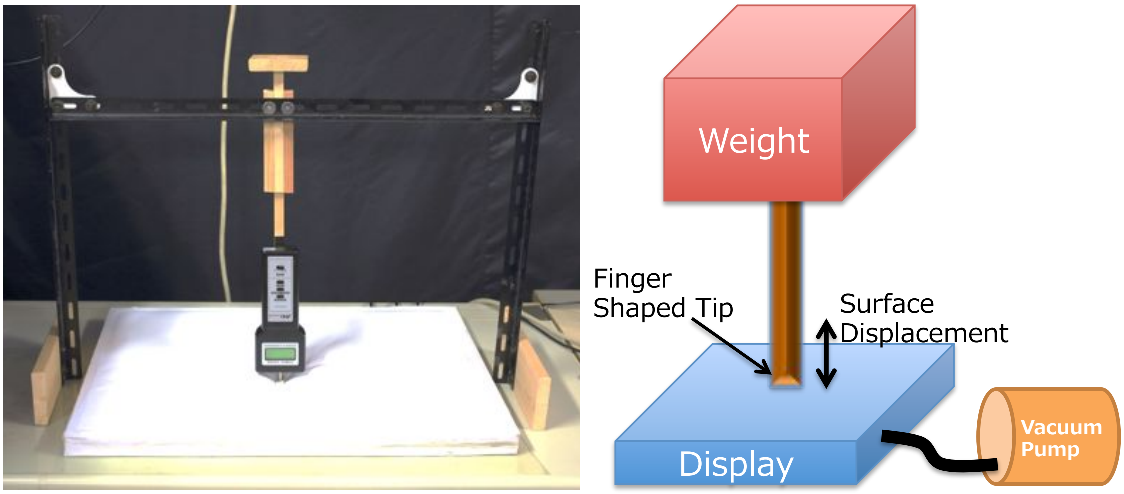

Figure 3.5: Pressure vs softness ecperiment setup

For measurement, we used an oval shaped acrylic plate and fixed it to the end of a single dimension pressure sensor rod that is then pressed into the display. The plate size was decided by measuring the index fingers of 10 university students. For the pressing force, we considered 2 types of pressing methods: light touch and hard press. These pressing force were also decided with user study by measuring the pressing force of 10 univertisty student when asked to touch force gauge lightly as also to press it hardly. Based on this user study, the average force of light touch is 1.5kgm/s^2, while the hard press is 4.5kgm/s^2. Figure3.6 show the result of these measurement.

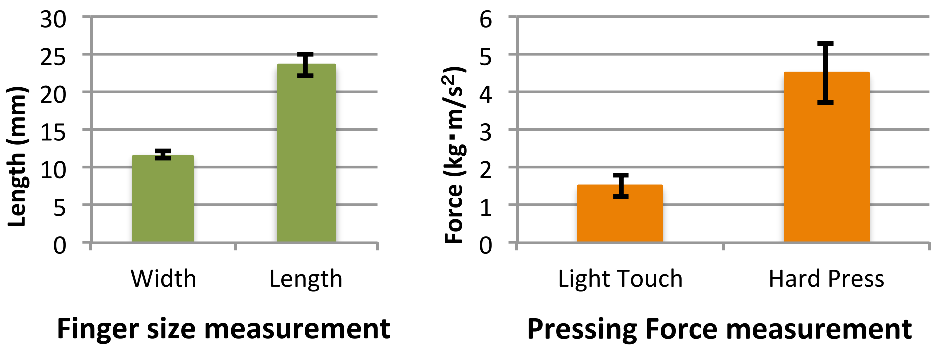

Figure 3.6: Finger size measurement results

Each weight was added as the force to weigh down the rod for 5 seconds, and displacement of the rod was taken for each measurement. The display pressure was decompressed in steps of 0.12kPa from -18kPa to 0kPa. Figure 2 shows the results of the experiment.

The following observations can be seen from the results. The display becomes harder as the internal pressure decreases, however a shift of about 2-5 mm was found to be always occur even when the pressure is at maximum pressure (limited by vacuum pump: - 18kPa). It could be considered that the factor influencing the shift was due to the soft characteristics of particles and surface fabric material. These characteristics show us the limitation of our system softness: when the pressure falls below a certain value, the display will not become any harder. To improve this limitation, further consideration of using alternative materials for the

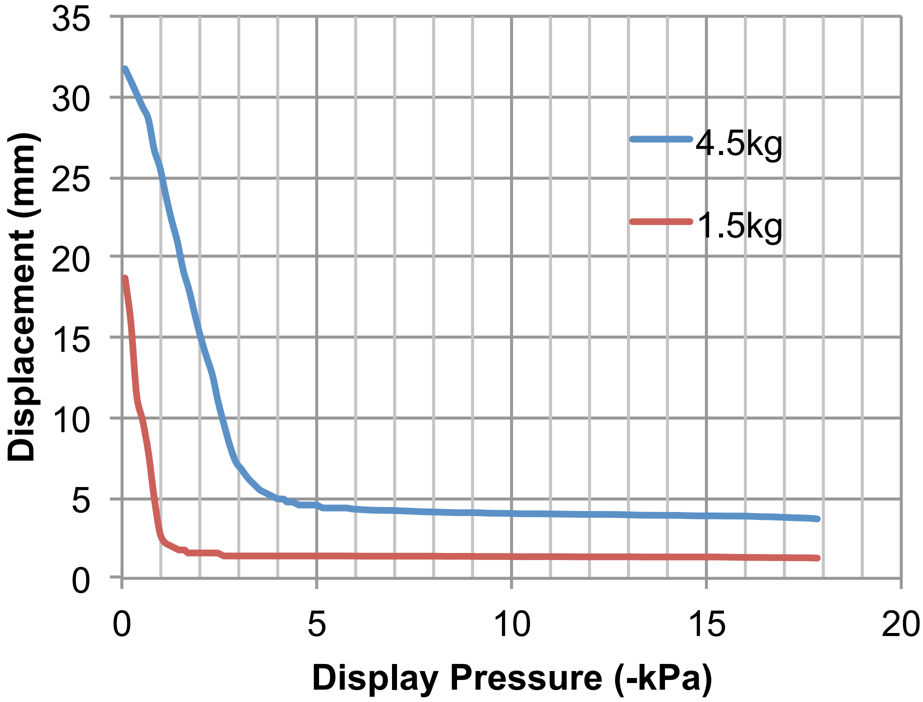

Figure 3.7: Display Displacement vs Internal Pressure graph

internal filling (particles) as well as the surface material should be made.

Also, the transition change is significantly smaller when the display pressure is below -2kPa in the case of a weak press, or below -4kPa in case of strong press. To achieve the plateau point, a vacuum level of -4kPa is suggested, which can easily be achieved by an inexpensive vacuum pump (10USD). This suggests that it is inexpensive to prevent substantial shape changing due to finger pressure as the vacuum demand is not great (-4kPa is ideal).

Based on these obeservation, we can conclude the polystyrene particles selected for our display has caractheristics as follow:

- Resistance change to hard hand press load varied from 32mm to 4mm in surface displacement.
- Resistance change to soft finger touch load varied from 19mm to 2mm in surface displacement.

- Controllable surface displacement change with minimum resolution of 4.55mm for hard press load.
- Controllable surface displacement change with minimum resolution of 1.9mm for soft touch load.

Chapter 4

Implementation of Display with Controllable Softness

We identify the requirements of our system as follows:

1. The surface is able to present the gradual dynamic translation of stiffness properties from soft to hard and vice versa.

2. The user can use the surface as a traditional planar surface as also as a 2.5-dimensional non-planar surface.

3. The user is able to change the surface shape using direct user interaction (hand interaction) and fix this deformed shape on the surface.

In order to achieve a display that meets these requirements, we developed prototype system called "ClaytricSurface", an interactive display with controllable stiffness properties. Here we describe the implementation of our system.

4.1 Hardware configuration

Figure 6.6 describes the hardware configuration of our prototype system. This system consists of: Display unit, Pressure control unit, Camera-projector unit.

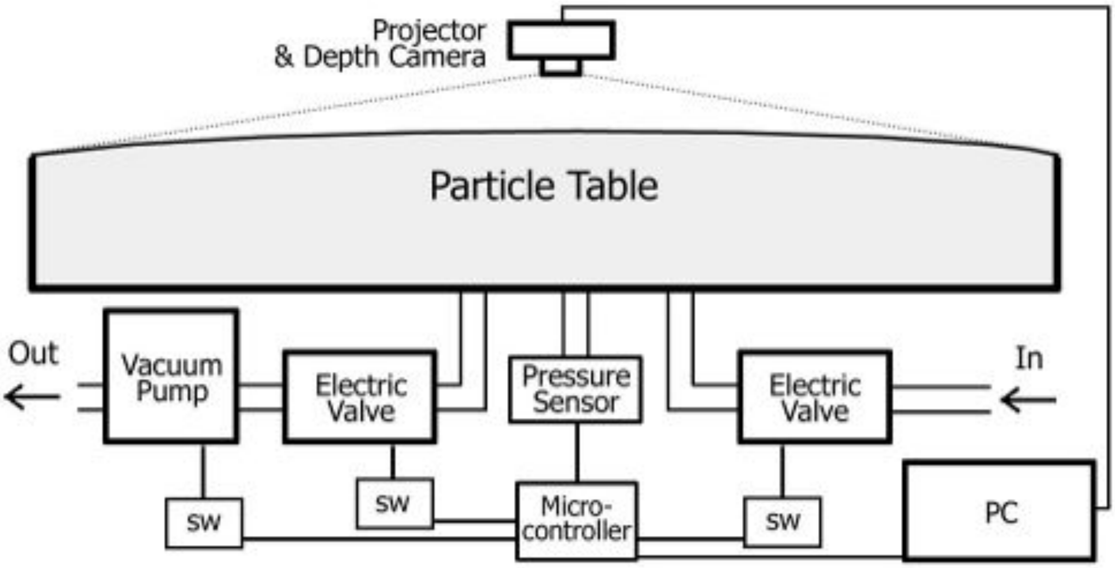

Figure 4.1: Hardware Configuration

4.1.1 Display unit

The display unit is composed of 655mm x 505mm x 35mm box frame made of wood, filled with 1mm expanded polystyrene particle. It is then covered and sealed with non-breathable spandex material. The spandex allows for elasticity in the vertical and horizontal directions. Additional rubber material is attached to the back of the fabric to further increase the airtightness. The display is then installed with three nozzles for compression, decompression and connection to sensors.

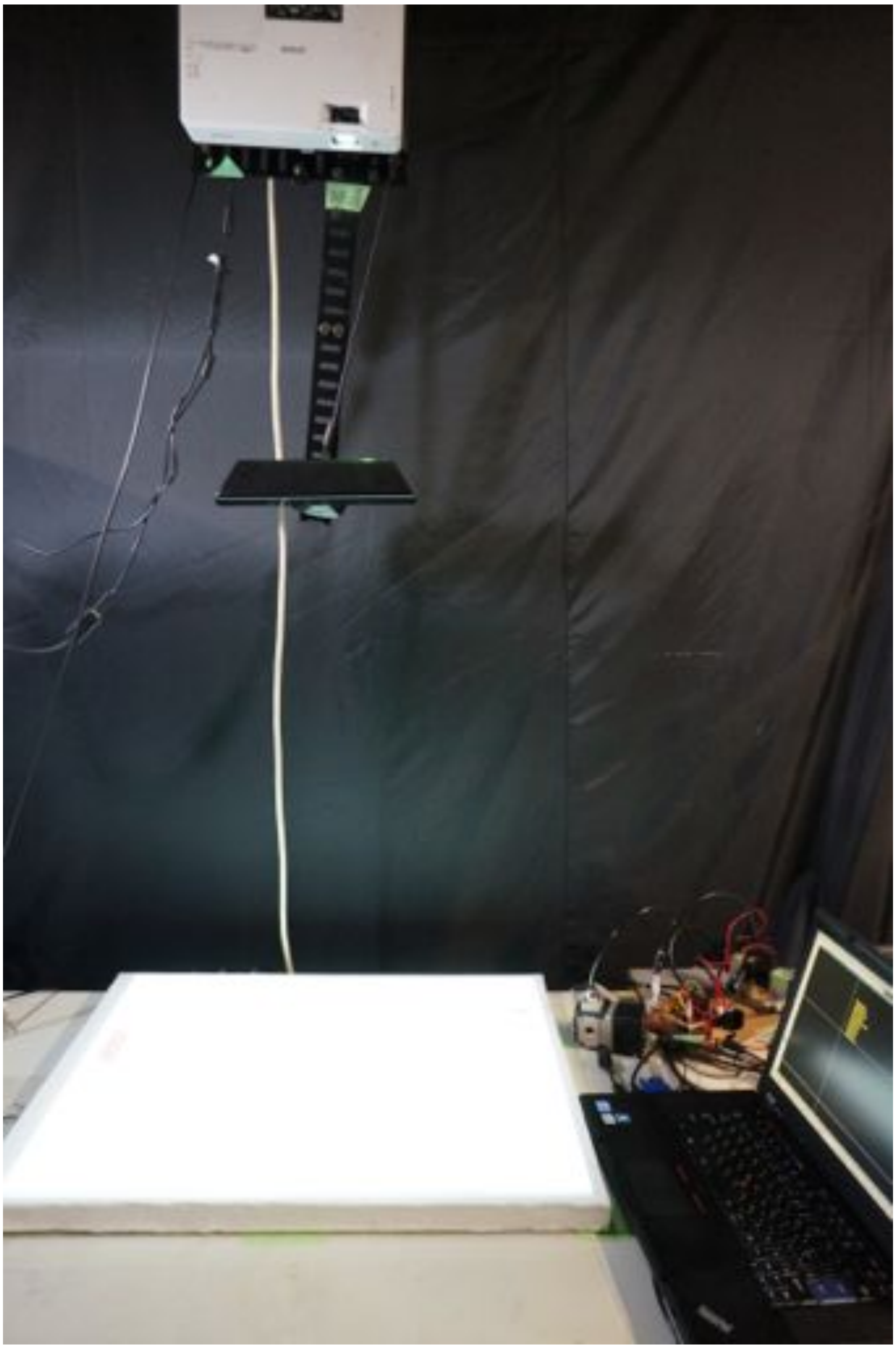

Figure 4.2: Configuration in appearance

4.1.2 Pressure controller unit

The Pressure controller unit is generally consist of 4 parts.

- Vacuum pump : vacuum source to decompress the display.

We use Medo VP0625 a linear motor piston pump that has pump speed of 40L/min and maximum vacuum level attainment of -33.3kPa.

- Solenoid valve : to control the pressure.
  We use CKD 3PB2 3 ports solenoid valve that has maximum vacuum durability to -100kPa. This solenoid valve working voltage is DC 24V, controlled with 5V relay circuit connected into micro controller.
- Pressure sensor: to monitor the display internal pressure.
  We use Fujikura XFPN-03PGVR pneumatic pressure sensor that can measure relative pressure from atmospheric (0kPa) up to -24.5kPa.
- Electronic vacuum regulator: to control the vacuum speed.
  We use CKD EV2100V that control range from atmospheric (0kPa) up to -101.3kPa.
- Micro Controller: to control and connect the pressure controller unit into the PC.
  We use Arduino Uno that has A/D conversion resolution of 10 bit and clock-speed of 16MHz.

Each of the pressure controller are linked with a 4mm inner-diameter tube. Figure 4.3 our pressure controller unit in appearance.

4.1.3 Projector and camera

As graphical output, we used a projector(Epson EMP-1715) that has resolution of 1024x680 pixels mounted at about 1.5m above the display. Also for touch detection purpose, we use Microsoft Kinect, a light coding based depth-sensing camera that has resolution of 480 x 640 pixels and frame rate of 30fps. The light coding technology is based on a PrimeSense design, projects a fixed pattern of infrared light. An offset infrared camera is used to calculate the precise manner in which this pattern is distorted as a function of the depth of the nearest physical

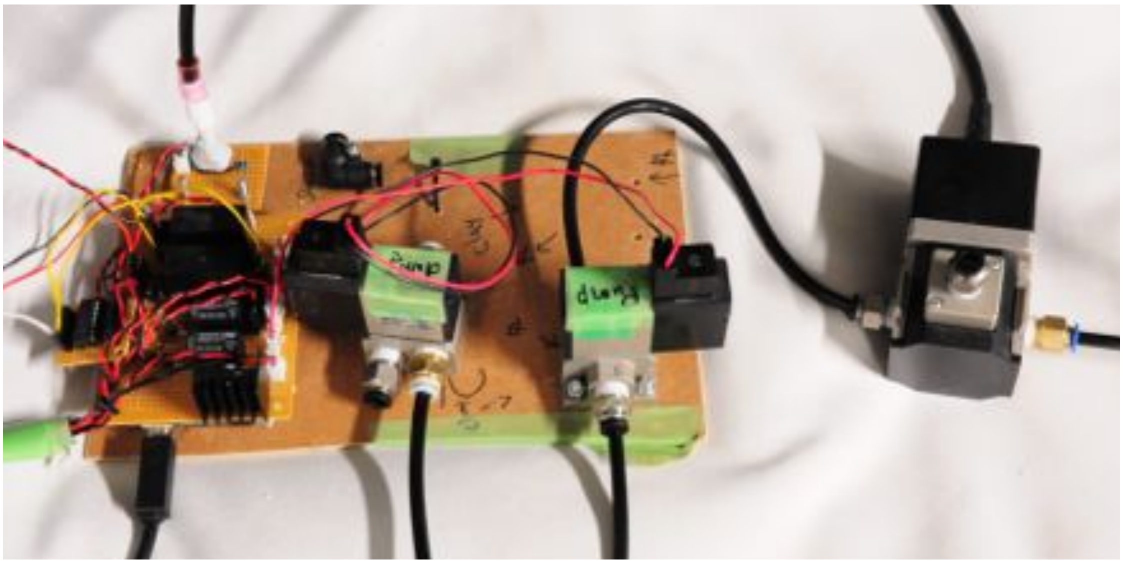

Figure 4.3: Display Displacement vs Internal Pressure

surface. Because the depth calculations are based on triangulating features in the image, depth precision decreases as the distance from the camera to subject increases. In this case we mounted the camera at 0.7m away above the display, based on the measurement by Smisek et. al[32], the depth resolution is about 1.3mm.

4.2 Stiffness control system

In this system, the display pressure can be changed and controlled by choosing available pressure settings offered by the system. In this prototype system, the pressure setting available are ranging from 0kPa to -18kPa, with interval of 0.027kPa. The pressure set are then sustained and adjusted using additional pressure control measures.

4.2.1 Ideal configuration control system

Assuming that the system in perfectly airtight, the set up pressure is attained by the adjustment of air pressure through: the increase of pressure via the opening of a solenoid valve connecting to ambient air (compression), and the decrease of pressure via a vacuum pump (decompression). Figure 4.4 show the flow chart of the pressure control algorithm.

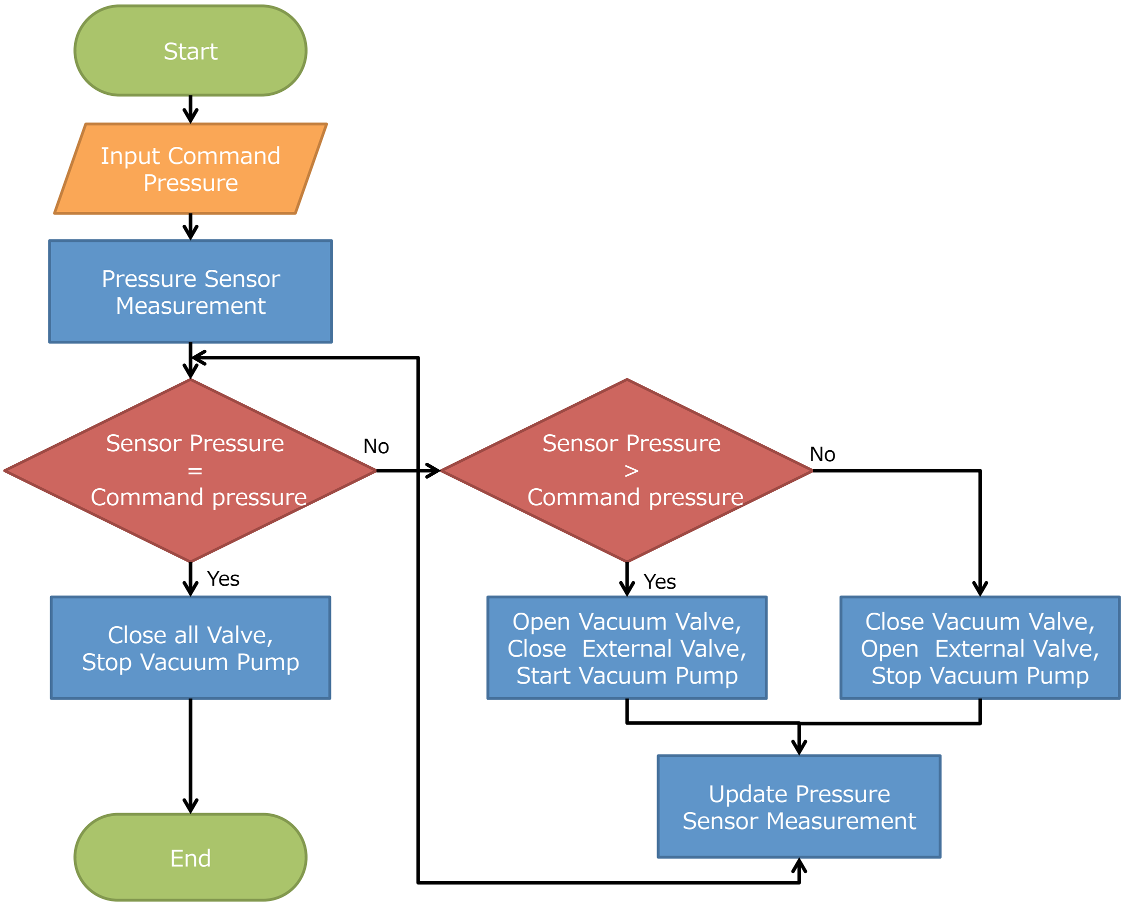

Figure 4.4: Pressure control flow chart

First, after the setting pressure is inputted, the system then compare it the pressure monitored from the sensor. If the sensor pressure is higher than the setting pressure, the system will switch on the vacuum pump as well open the solenoid valve connecting the pump into the display, starting decompression of the display. Meanwhile, if the sensor pressure is lower than the setting pressure, the system will open the solenoid valve connecting the display into the ambient air, letting the air flow into the display due to pressure difference. Otherwise, if the sensor pressure is matching the setting pressure, the display pressure will be kept by closing all solenoid valves connected into the display. Figure 4.5 show, the actual display stiffness change.

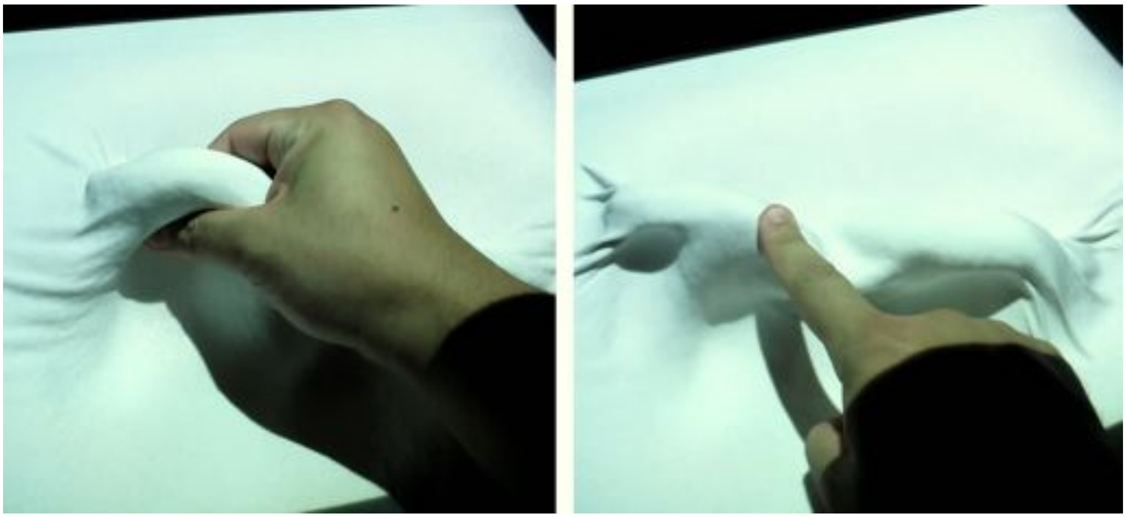

Figure 4.5: Left: display at soft state (0kPa), right: display at rigid state (-18kPa)

4.2.2 Air leakage countermeasure

However, in practice, the display experiences an amount of air leakage due to the un-airtightness of the configuration, eg: small hole in spandex material, untight connection between pressure controllers unit, etc. Therefore the pressure can not be kept even when all of the solenoid being closed. This air leakage also cause the maximum vacuum level can be attained by the system drop into -18kPa (the capability of the vacuum pump is up to -33kPa). This air leakage is then resulting unstable pressure change when the system trying to keep the setting pressure. Figure 4.6 show how the monitored air pressure change when the system trying to maintain the pressure at -36kPa.

Figure 4.6 show when valve is closed, the pressure start to increase due to air leakage, then the system will start to decompress again, making a wave-like change in pressure. This repetition of compressing and decompressing is also resulting a noisy system where the solenoid valve and vacuum pump actuate and unactuated repetitively.

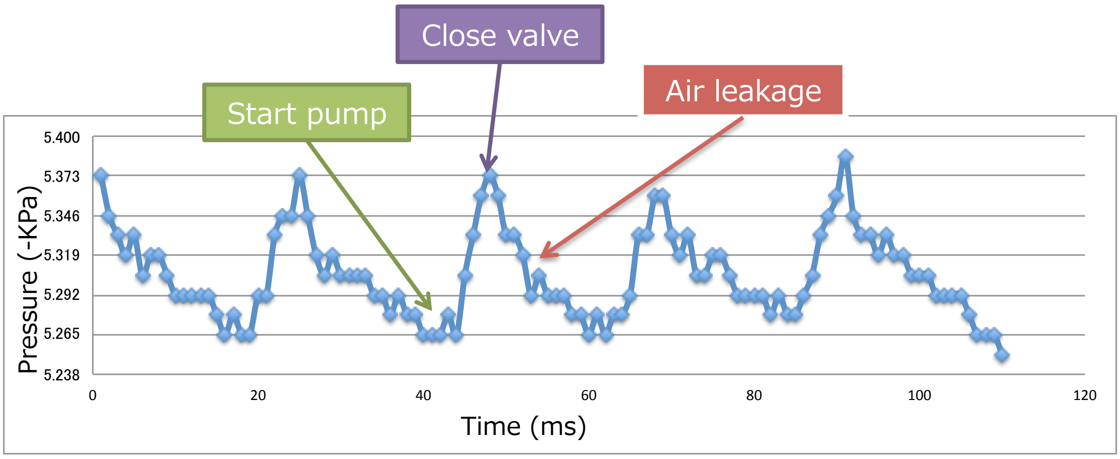

Figure 4.6: Pressure change due to air leakage

To counter measure this shortcoming of both noisy and unstable system, we also implemented an electronic vacuum regulator based pressure control into the system. Using this electronic vacuum regulator, we were able to kept the pressure stabile and stop the solenoid from repetitive actuation. In addition using control algorithm as shown in figure 4.7, we were also able to control the speed of pressure decompression as also pressure compression.

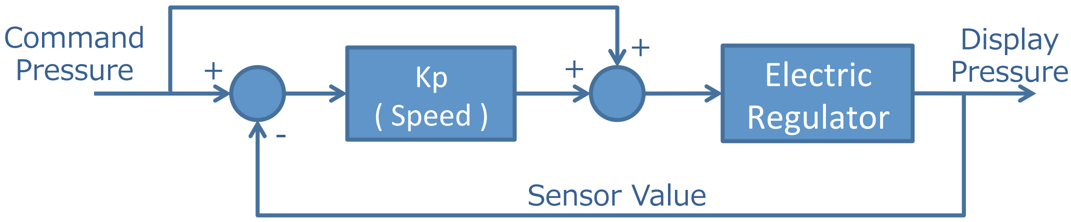

Figure 4.7: Electronic vacuum regulator control

Changing Kp with positive value will make a faster compression or decompression. In contrast, changing the Kp with negative value, resulting in a slower compression or decompression.

4.3 Depth camera based Input System

As one of our system requirement is a direct user interaction (hand input). In this research, we implemented a multi-touch detection using a depth camera mounted 1m above the surface. We build our touch detection system based on technique introduced by Wilson et. al[39]. We chose this depth camera based input technique due to the following reason:

1. Simple and easy to implement.
   We do not need to fabricated any sensor into display surface.
2. Applicable for non-flat surface.
   One of our surface objective is to allow hand interaction in both flat and shaped state.
3. Multipurpose.
   Other than touch detection, the depth data can also be used for other use and application, such as 3D shape scan, and object detection.

In practice, though wilson et. al method allow a multi-touch detection on non-flat surface, it does not cover a dynamical change in surface shape, which is a very important factor of our display surface. Therefore, in this implementation we also propose a new method that allow touch detection on dynamically changing surface. Figure show the flow chart of our touch detection algorithm.

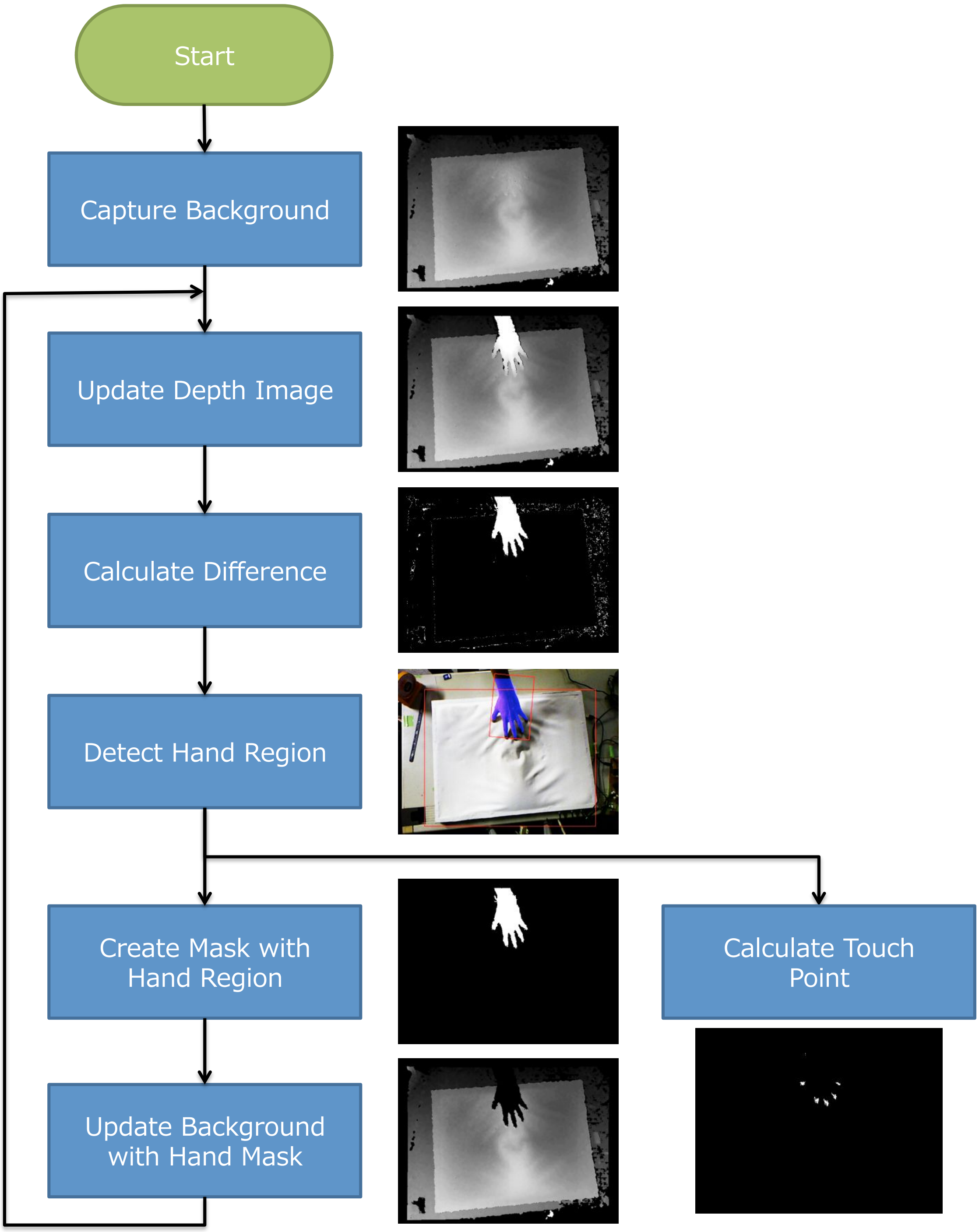

Figure 4.8: Touch detection flow

4.3.1 Touch detection based on depth data

One of this touch detection limitation, is that this method can not detect the real finger contact with the display. Instead, this method is using an approximation of the touch point based on the depth of finger surface (as seen by camera) compared to the touch surface. Figure 4.9 show how the touch is defined in this method.

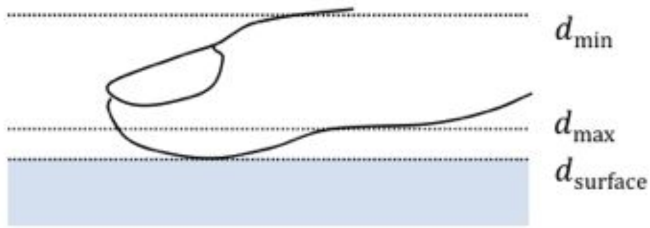

Figure 4.9: Finger touch segmentation

Basically, the touch identified when the finger surface measured is closer than $d_{surface}$, but further than d_{min} threshold. However, to eliminate misdetection due to depth error measurement, a second threshold d_{max} is also used. Therefore the relation is defined as:

$$d_{max} > d_{x,y} > d_{min} \tag{4.1}$$

The approach outlined above relies on good estimates of the distance to the surface at every pixel in the image. The value of d_{max} should be as great as possible without miss-classifying too many non-touch pixels. The value can be chosen to match the known distanced $d_{surface}$ to the surface, with some margin to accommodate any noise in the depth image values. Setting this value too loosely risks cutting the tips of fingers off, which will cause an undesirable shift in contact position in later stages of processing. Based on few trial, for our current implementation the the best d_{max} value is 5mm (bigger than Kinect depth resolution : 1.3mm).

Setting d_{min} is less straightforward: too low of a value (too near) will cause contacts to be generated well before there is an actual touch. Too great of a value (too far) may make the resulting image of classified pixels difficult to group into distinct contacts. Setting d_{min} too low or too high will cause a shift in contact position.

4.3.2 Touch detection for non-flat surface

To be able to detect touch input on non flat surface, the system need to first create a surface model when the surface is empty. The touch at current frame is detected then, by calculating the d_{max} and d_{min} relation (6.1) at each pixels of the surface. Figure 4.10 show how the touch detected on our shaped surface.

The background image is initialized by taking depth image when the surface is empty (fig.4.10 left). The user hand area (fig.4.10 upper right) can be detected by subtracting current depth image (fig.4.10 center) with the background image. Next, touch area is identified by binarizes regions only within the range of 5mm(d_{max}) to 15mm(d_{min}) from the surface 4.10 bottom right). Finally, the touch point determined by calculating the centeroid of touch area that has some certain size. This method allow for multi touch as long as the finger not obsecured (fig.4.11).

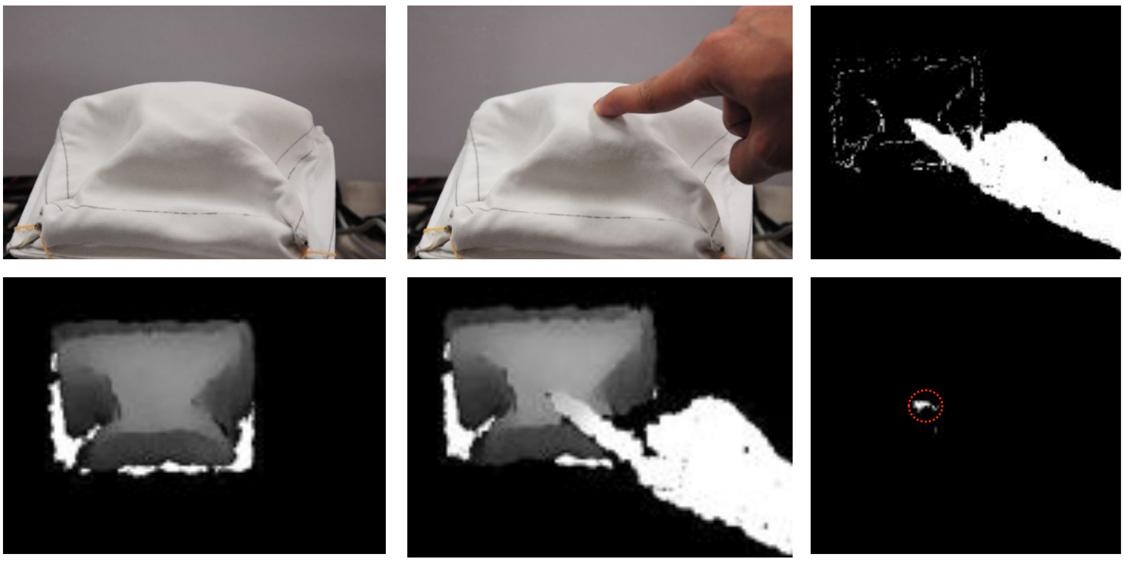

Figure 4.10: Left: Background image, Center: Finger touch, Upper right: Hand area, Bottom right: Touch point

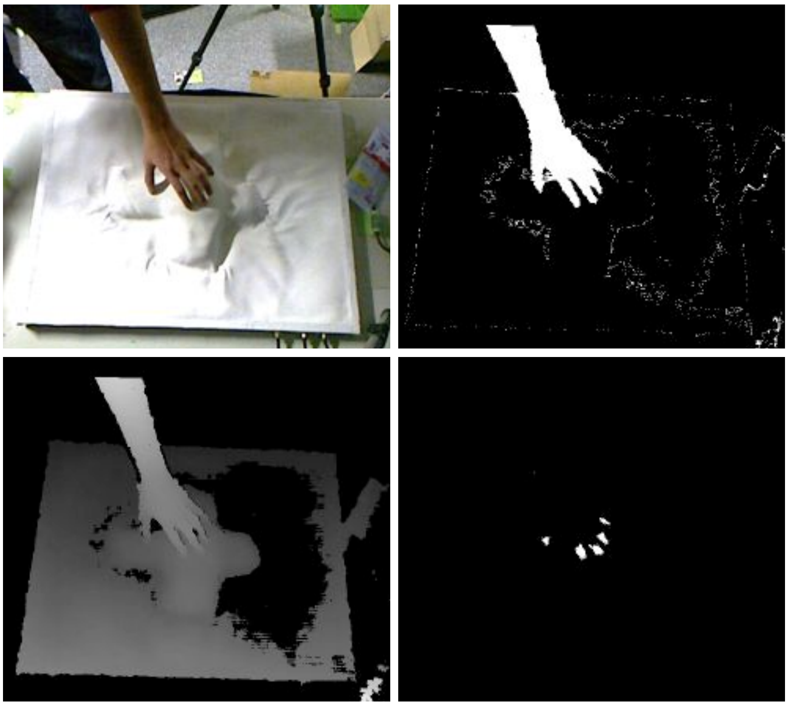

Figure 4.11: Multi finger touch detection

4.3.3 Touch detection for shape changing surface

However, because our surface can be soft and deformable the surface shape and thus the background depth data can actively change due to direct user input. Therefore the approach explained above alone will not sufficient to implement touch input on our deformable surface. Figure 4.12 show how the shape change affected the touch detection.

To overcome this problem, we also developed a method to adaptively updating the background image at each frame. When the surface is empty, the system will automatically renew the background image at each frame. However, when user is manipulating the surface, their arm will obscured part of the background surface. Therefore, the user arms need to be distinquished from the background surface first, then the area excluding user arm can be updated as new background image. Figure 4.13 and show how the background is updated while user manipulating the surface.

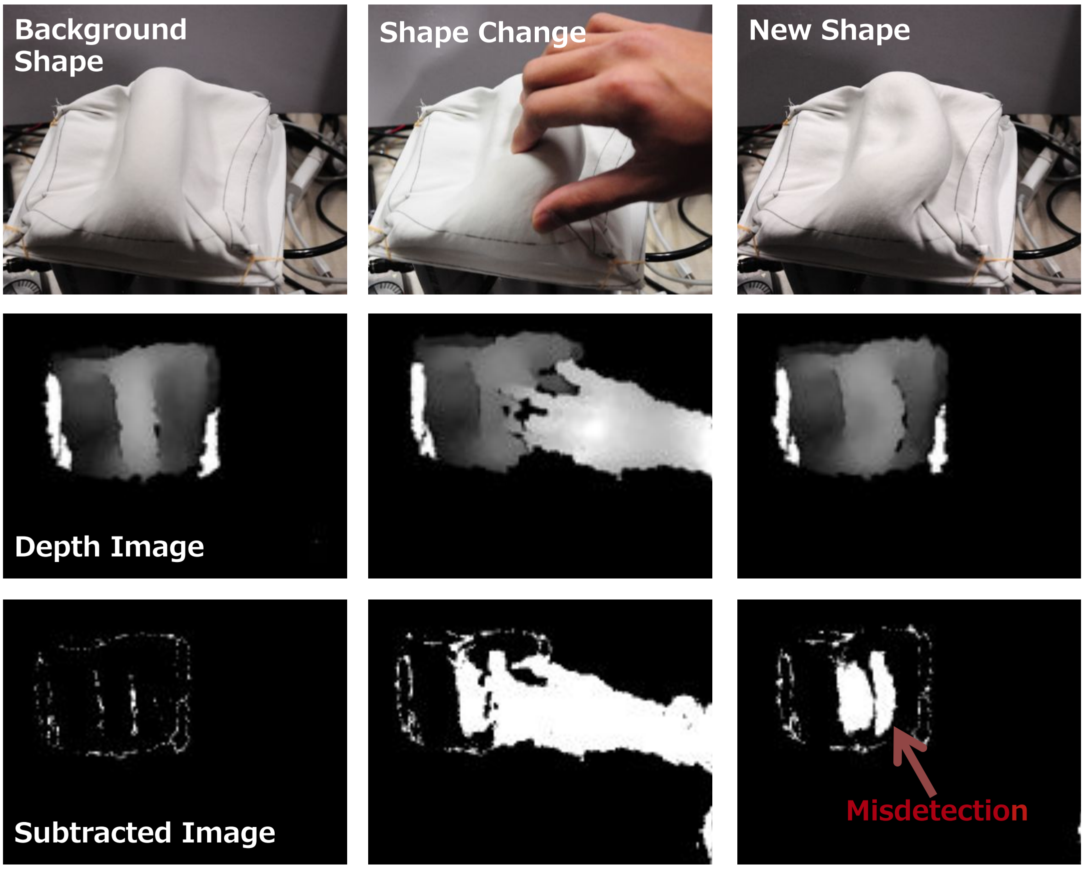

Figure 4.12: Shape deformation problem

First, the user arm is detected as an areas that not fully enclosed by background values and seems to extends in from outside the display into the inner boundaries of the display (fig. 4.13 upper left). This approach was already described by Harrison et al. in [7]. Then an exclude mask created using the detected hand area(fig. 4.13 upper right). Next, we exclude this hand area from the current frame depth image(fig. 4.13bottom left). Finally, the latest background is updated by masking previous background with the current frame with no hand area. The sequence of this updating process can be defined as following:

$$I_{background} = (I_{depthimage} - I_{handmask}) + (I_{background-1} \& I_{handmask}) \tag{4.2}$$

Figure 4.13 show how our proposed method allow an adaptive background update despite the hand occlusion at every frame.

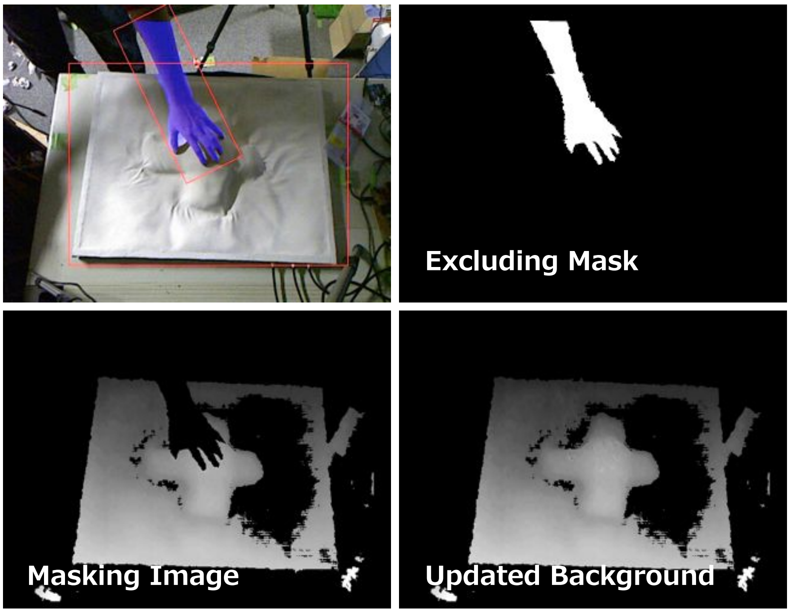

Figure 4.13: Background update

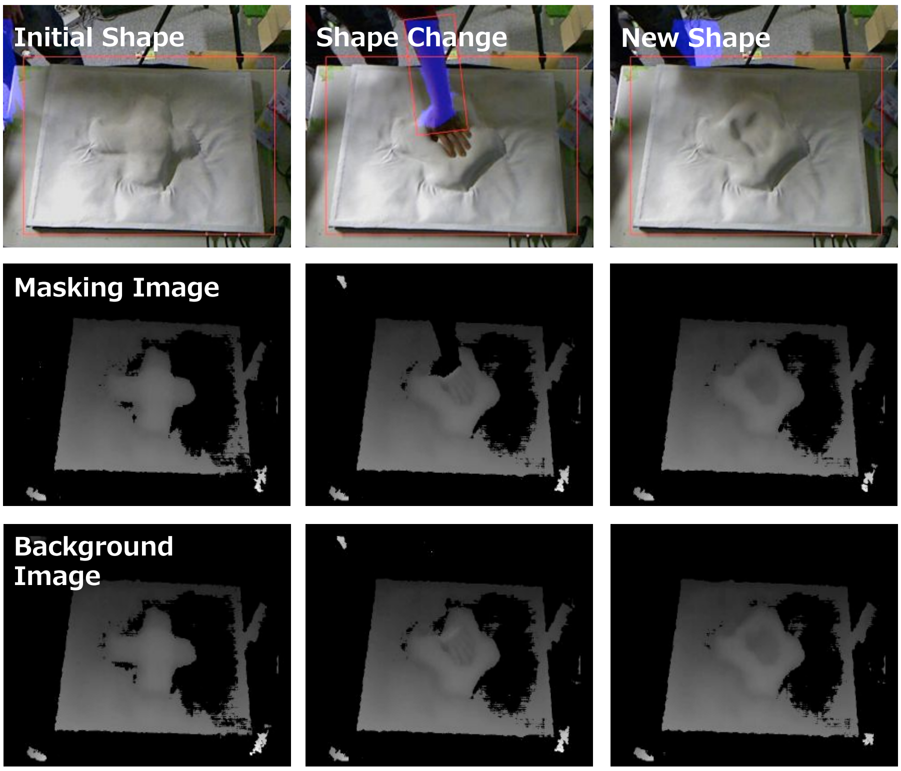

Figure 4.14: Display deformation with background update

4.4 Pen Input Detection

Other than direct touch input, we also consider using a tool such as pen for the display input interaction. For this purpose, we also implemented a pen tip detection using pen tablet placed under the display. For the detection, we use an inductive based tablet device(Wacom Intuos4) that can sense a stylus pen coil up to 2 cm above the device. Thus, we also build a specialized particle display with thickness of 1cm and placed the stylus tablet under the display (Figure 4.15). Using this configuration, the device can detect the pen touch location through the display even when the surface is not flat.

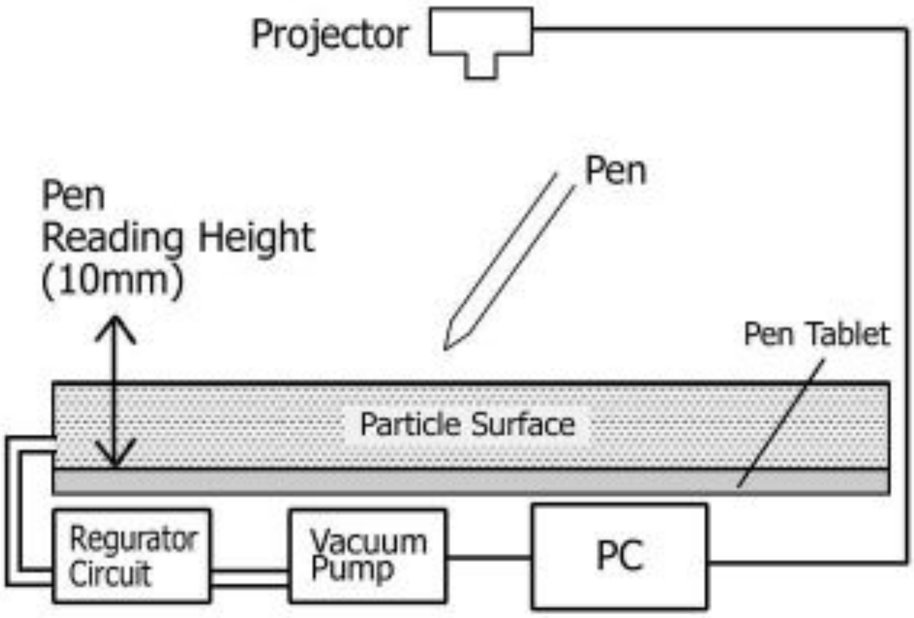

Figure 4.15: Pen input hardware configuration

4.5 Pressure sensor based gesture detection

As described at the softness control section, in this research we use a vacuum pressure sensor (Fujikura XFPN-03PGVR) as feedback control of the display pressure. However, we found that the monitored pressure value can also be utilized to detect the user hand manipulation (due to the capability of pressure sensor to measure small pressure change up to 0.027kPa). In this case, the softness control required to be set as keeping at soft pressure state (0 - 1kPa). Here we define 3 types of interaction that can be detected based on the pressure change and the touch detection output.

4.5.1 Pressing gesture

Contrary to the pulling gesture, when the user depressed display surface, pressure inside being compressed from the stress. Therefore, we can identify this pressing gesture as a positive jump in display pressure and touch detection as shown in figure 4.16.

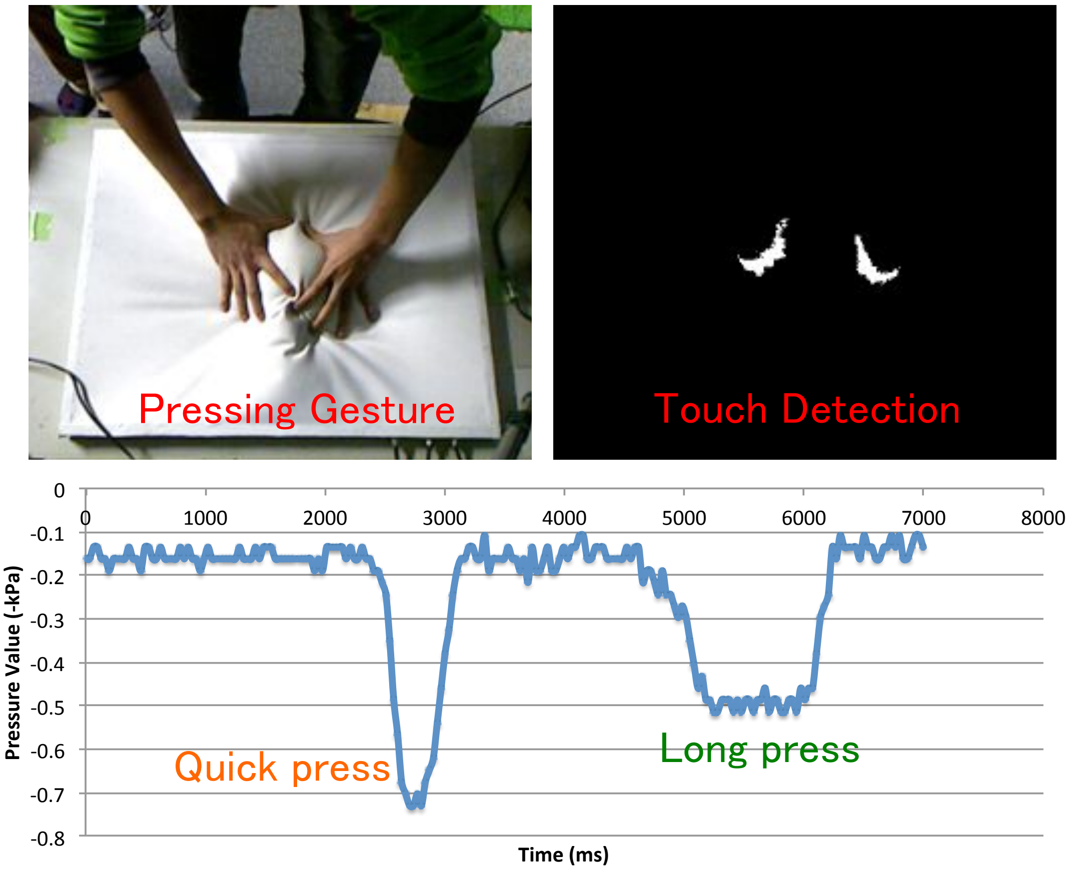

Figure 4.16: Pressing gesture detection

4.5.2 Pulling gesture

When a user pinching and stretching out the surface cloth, pressure inside the display is decompressed due to the sudden expansion in display volume. Using this reaction, we can successfully identify the user pulling gesture when the system detect both this negative pressure jump(fig. 4.17 bottom) and user touch detection (fig. 4.17 upper right).

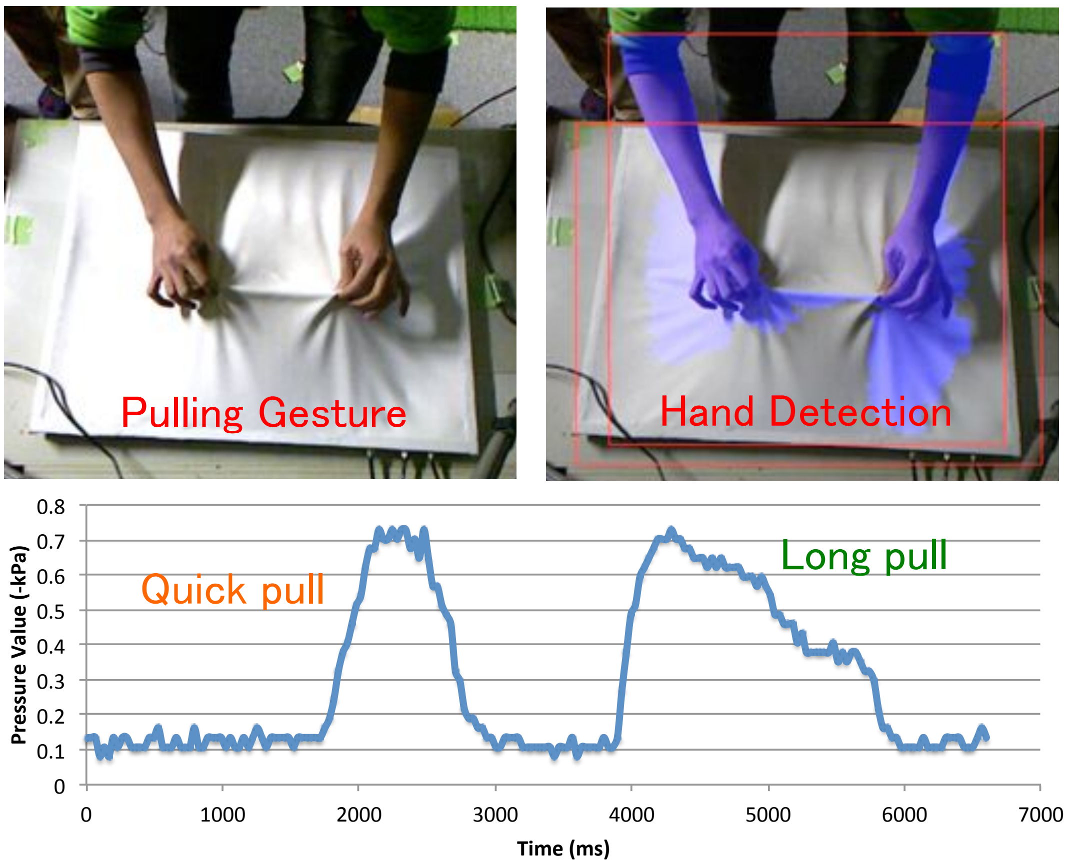

Figure 4.17: Pulling gesture detection

4.5.3 No-force touch gesture

Aside from the fluctuation, the static state in pressure value can also be a useful information in determining user input operation. In this case, we can we distinguish when the user softly touch the display without changing the display shape, as the system detect touch input with no fluctuation in sensor value(fig. 4.18.

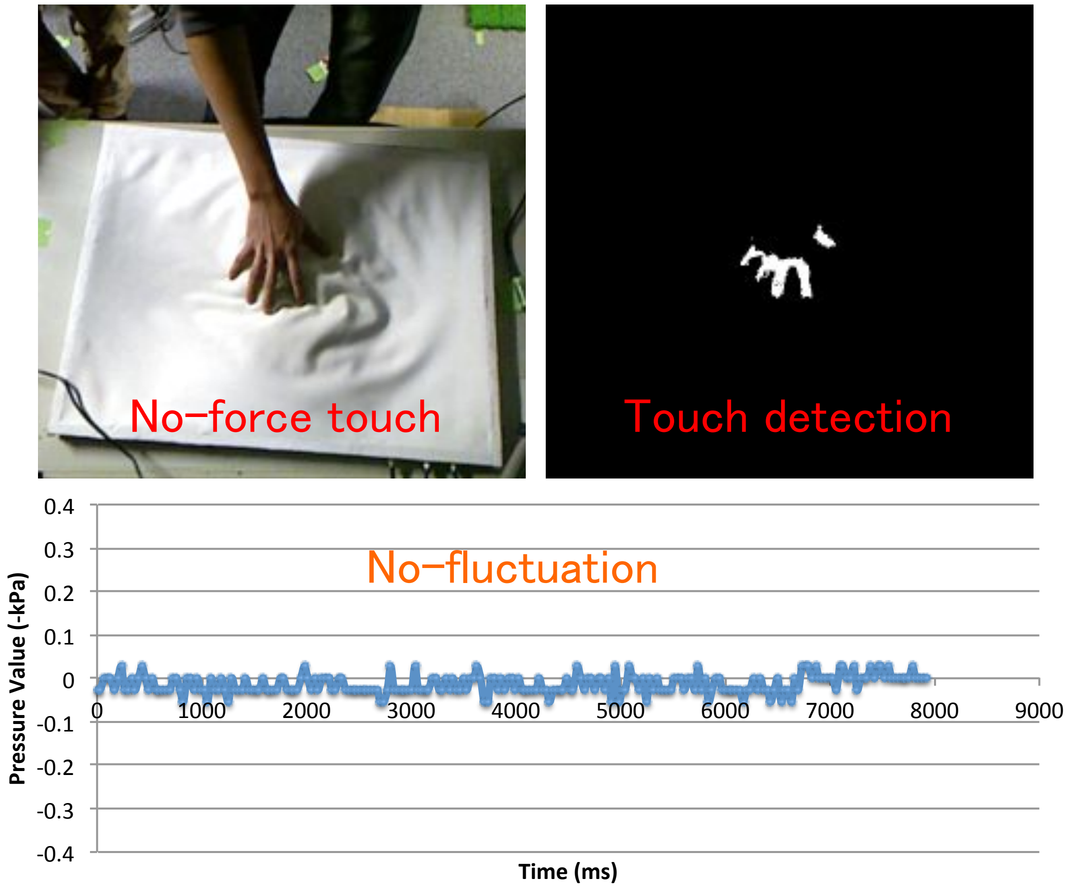

Figure 4.18: No-force gesture detection

Although this feature is in an early stage of development, we have identified several ways this gesture detection could be utilized eg: to detect user deforming works or to control display softness. In addition, the amplitude of pressure change is directly related to surface displacement distance. Shallower presses or pulls yield smaller pressure change, while deeper ones produce higher pressure fluctuation (Figure 4.19). The force required to depress the elastic layer increases as it is stretched (Hookefs law), and so displacement distance (and thus pressure) is directly related to press force.

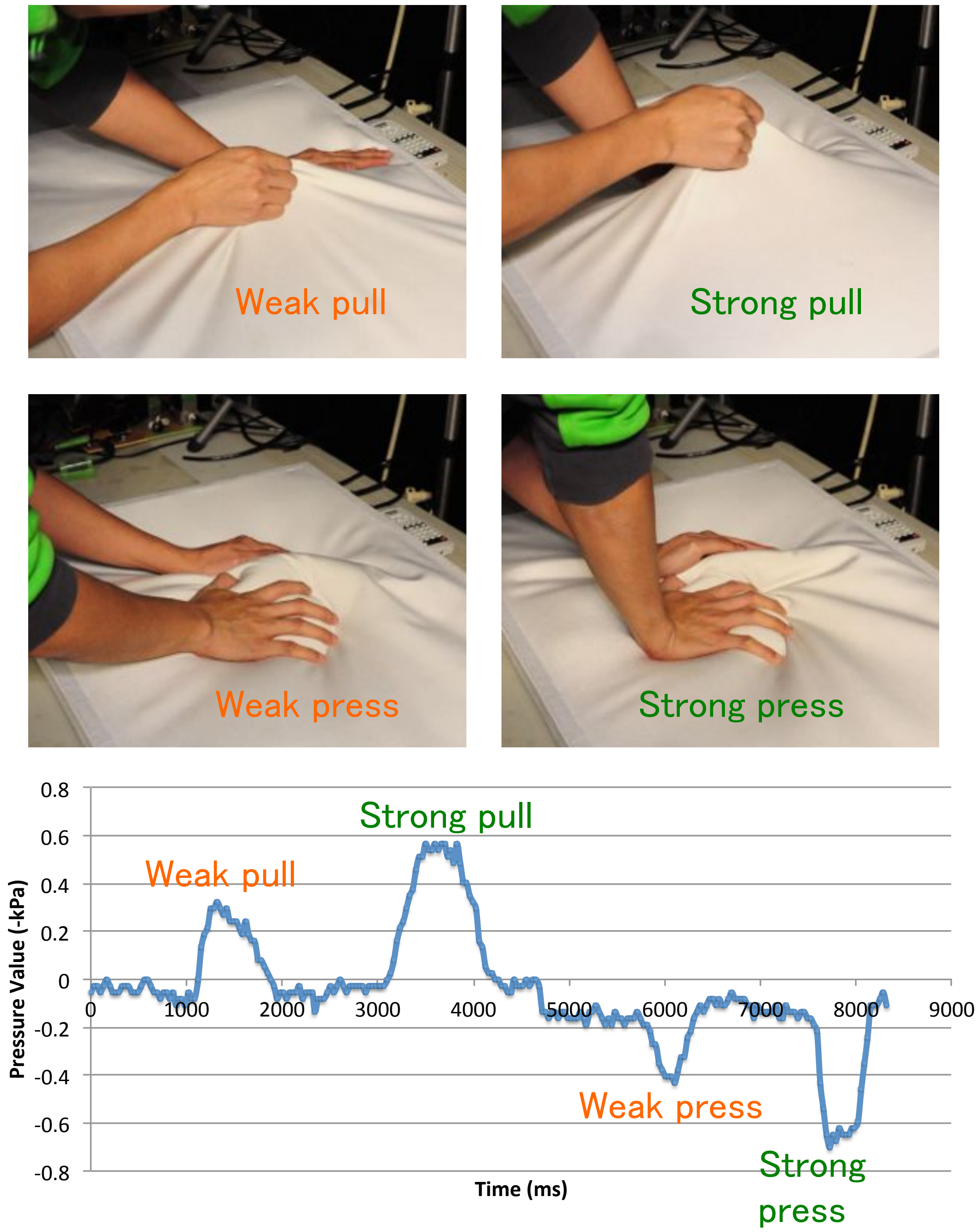

Figure 4.19: Press and pull force change

Chapter 5

Controllable softness display for Modeling Tools

In comparison with other interactive surface, we identified our surface has following advantages:

1. Capability to control surface softness with precision.
   On the current implementation, we were able to control precise pressure at unit of 0.0.27kPa and surface displacement at average of 1.28mm.

2. Direct touch input on the surface, regardless of the change in the shape.
   We also have evaluate the usability of our touch detection on variable shape and describe the details on evaluation chapter.

3. Variation in surface elasticity and spring force.
   The surface show both a high elasticity(due to surface material) on soft state, and very low elasticity on stiffer state.

4. Capabilities to imitate a clay-like tactile sense
   Due to the jamming stiffness change and the spandex material spring force properties, at certain pressure level, combination of both of these characteristics resulting in a viscousness and stickiness feel of a clay.

Considering all the characteristics mentioned above, we developed a ”2.5-dimensional shape modeling tools” as an application to demonstrate the usability of our surface. This application allows the user to design a 2.5-dimensional shape that can be deformed directly by kneading a display surface with both hands. The shape can then be fixed by changing the stiffness into the rigid state. In addition, combining with the surface touch detection and graphical projection, it also possible to draw textures on top of the surface. For the first step, in this research we build a prototype modeling tools that can be use for entertainment.

5.1 Softness control Interface design

Since the purpose of our application is for entertainment, the user interface is required to be intuitive and easily understandable. Thus, we proposed a simple slider and buttons for GUI control. This GUI that can be operated with touch input directly on display surface. We also included a 4-step tutorial that enables navigated control for beginners, and gesture based control to help a modeling operation with both hands.

5.1.1 Slider and Button design

In this system, stiffness level can be manipulated specifically with pressure control allowing for full range control from soft state (0kPa) up to hardened state (-18kPa). However considering the softness and pressure relationship as mentioned at chapter 3, the softness change is not linear to the pressure controlled. Therefore, to provide user with a smooth continuous softness change, we assigned the slider at different portion to disparate vacuum level, make it as linear as possible to the softness change. In this case, we use the relation data of measurement at 4.5 Kg (hard press). Figure 5.1 show the detailed assignment of the pressure to the slider portion.

In addition, we also designed 2 supplemental buttons that offer the user direct stiffness switching including "Soft Button"(assigned to 0kPa) and "Hardened Button" (assigned to -18kPa). Both of this button an slider GUI are projected into the display surface, and the user can then operate the GUI directly with touch

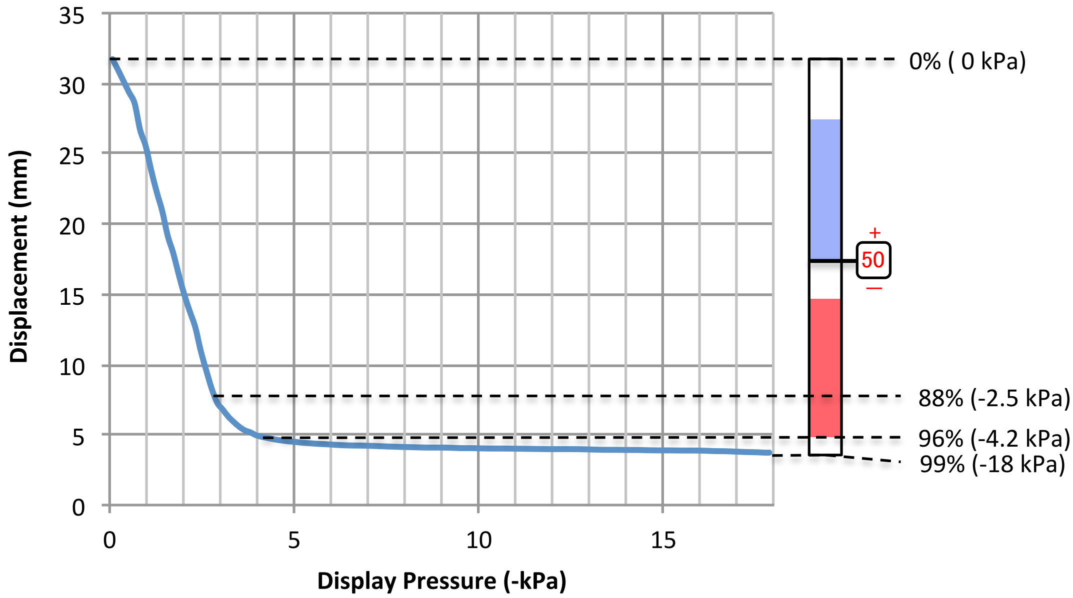

Figure 5.1: Pressure to slider assignment

input. We found that this capability of control the softness directly with touch input also has a merit in allowing the user to feel the softness change while operating the GUI. Therefore, the user can choose the suitable softness more intuitively compared to operating interface that separated from the display eg: mouse and keyboard. Figure 5.2 show the GUI view that projected into the display, and figure 5.3 show the actual scene when user operating the slider on the display.

5.1.2 Gesture base freehand control

This system's softness control is operated using a slider or button. However, this was found inconvenient in the case of a modeling works with both hands due the user needing to release one hand to operate the UI.

Here we developed three different simple gesture based control methods to support modeling work that do not require button operation. This automatic control technique is implemented for the modeling application and could be activated or deactivated freely.

Initial hardening assistance

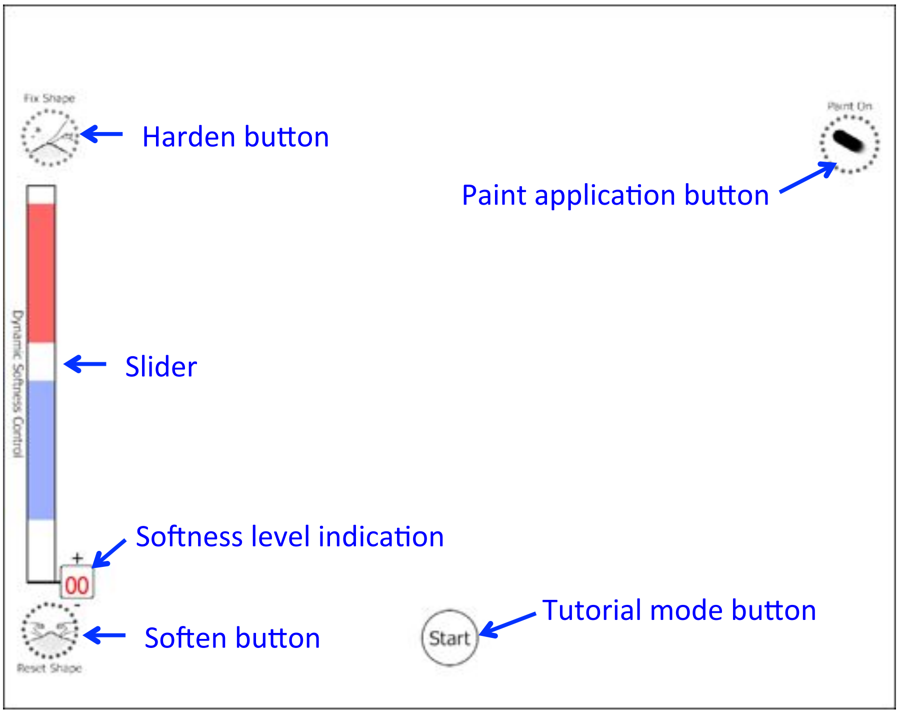

Figure 5.2: Projected GUI control

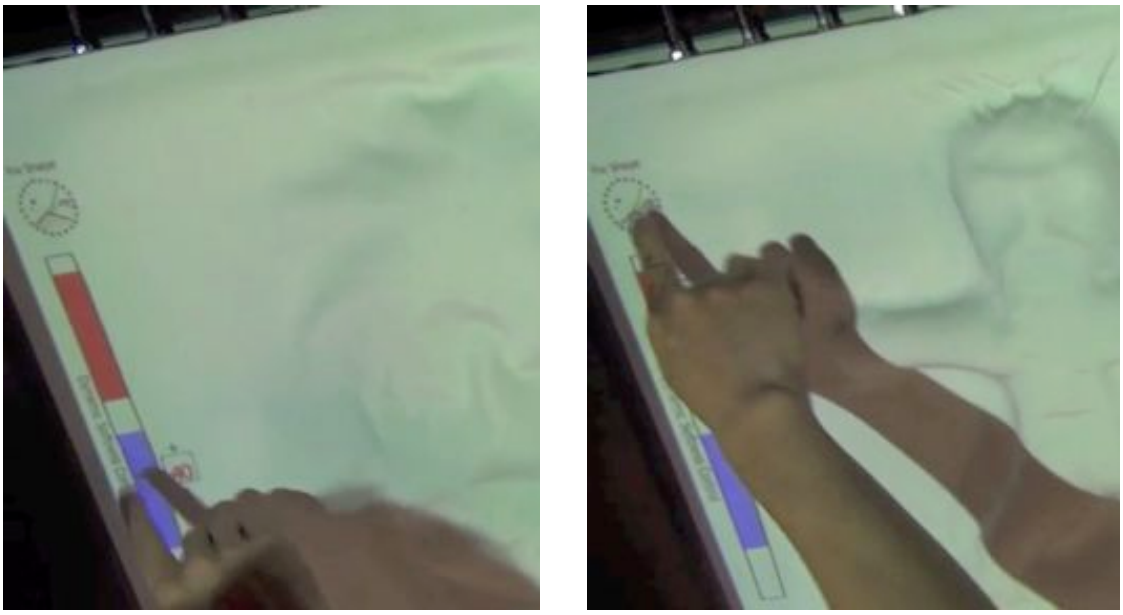

Figure 5.3: GUI operation scene

In modeling, users will first make a rough shape as the base of the model; to supper this, user will use the soft state of the display and gather the

Figure 5.4: From left to right: Initial Hardening Assistance, Pull up assistance, Reset assistance

necessary display material with both hands. However, to fix the base model they will then need to harden the display. This becomes a problem as users will need to support the base shape with both hands while operating the UI. Therefore, we developed a function detect user actions when the display is soft to automatically harden the display accordingly(5.4(left). The system is first detects if both user hand are in contact with the display and the display is in its softest state. If, after 3 seconds, the hands are still in contact with the display, and there is no fluctuation in monitored air pressure, it is safe to assume that the user is holding the shape in place and the system will automatically harden the display to maintain the user-created rough shape(-15kPa).

Pull up assistance

To create a shape with substantial height or one with overhanging sections, the surface needs to be pulled up little by little using both hands. However, higher shapes require higher stiffness levels to maintain the height, which is a very difficult challenge in this area. Therefore, we added a function to measure the model height with depth camera. If the user creates a model with substantial height and the monitored pressure level is decreased by more than 0.3kPa (due to pulling up of particles creating a 'suction' like effect in the volume), the system will change stiffness levels according to the model height

Reset assistance

When users want to reset the display and remove the shape from the surface, they will need to change the surface softness to soft and flatten the display with hands. Also, a more efficient way to reset the shape is to shake the display like sieving with both hands. In this system we add a function to detect the user hand movement when sieving the display with a accelerometer sensor built-in the display. The system will automatically change the stiffness into the softest state (figure5.4(right)). This stiffness change happens only when acceleration is applied, and the user can adjust the flatness with the applied strength.

Temporal change

We also introduced a function of stiffness changing with time. In this function we implement two types of modes. The first being is "Gradual Surface Hardening", and the second "Hardening after Countdown". This type of function can simulate a modeling work using real clay (such as curing, or drying), as well as adding entertainment element into the modeling process.

5.2 Modeling application

Our system is a projection-based display that has deformable surface. The surface stiffness is programmable and can be controlled by the user or by the system in real time. The user can also interact with the fixed surface not only by "touching" or "pushing", but also by "pinching" convex shapes that can be molded into the surface while experiencing dynamically changing tactile sensations. In this section, we describe two design tools for prototyping or entertainment use as first applications of our system.

5.2.1 Modelling works on variable stiffness display

Here we define the correlation of our display for modelling works

The physical behavior of the display surface is a correlation between the elastic force of stretched spandex material and the frictional force of the internal polystyrene particles under pressure. First, if the display is at atmospheric pressure, the display indicates the soft particles behavior that can be moved smoothly in the display (figure left). Therefore, users can easily move or gather particles from the above of the surface cloth with both hands. However, due to the restoring force of the cloth, If the user has made the shape that has height and fine detail, it causes the collapsing of shape when the user release their hands.

Then, as the pressure gradually reduces the friction force of the particles gradually become stronger. Due to the jamming stiffness change and the spandex material spring force properties, at certain pressure level, combination of both of these characteristics resulting in a viscousness and stickiness feel like those of a clay (figure center). In this state, the frictional force of the particles become stronger than the restoring force of the cloth, resulting the surface has enough tension to maintain its shape.

Finally, when the pressure is close to vacuum, the external stress due to the pressure different is high enough to deform each particle, resulting in closely interlocking particle chain, exhibit one rigid object properties(figure right).

However, in the case the shape has a detailed shape or has substantial height (including overhanged shapes), stronger vacuum is required to maintain the shape.

By considering the above properties, the suitable modeling style of this system is modeling using graduate softness changes from rough shape to detailed shape. This is not the same as cut and pasting like with actual clay modeling, but close to the sculpturing that gradually preparing the material.

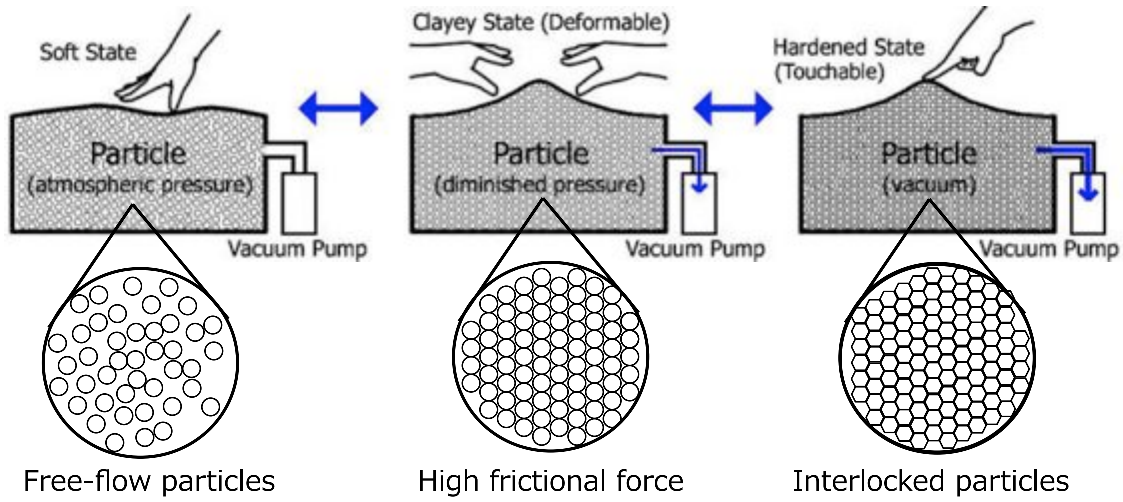

Figure 5.5: Particle display softness change

5.2.2 Modelling works procedure

To demonstrate our system, we developed shape modeling tool focusing on prototyping for entertainment use for our application. Our application enables the user to make the shape directly by hand rather than complex GUI actions required by a keyboard mouse in 3D modeling programs. Users are also able to apply texture by simply touching the shape directly with their fingers, much like painting a sculpture.

We define, the modeling procedure suitable for our display are as follow:

Rough shape modeling

Firstly, the user performs work to collect the first particle materials to create a rough shape. This rough shape is also used as a base shape for a more complex shape. This action will be easy to perform in low hardness state near the atmospheric pressure.

Detailed shape modeling

This work is to create detailed shape on the rough shape that is modeled in rough modeling state. In order to maintain the detailed shape on this system, it is necessary to set a higher hardness than the hardness of rough

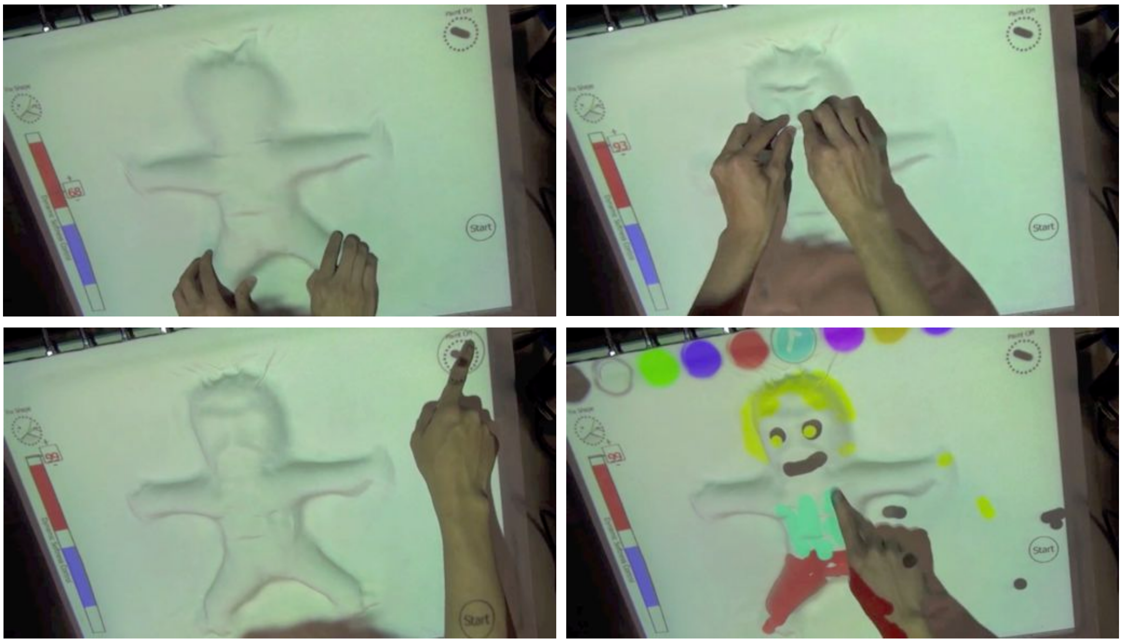

Figure 5.6: Modeling procedure

modeling state.

Fixing the shape

The next step is to then fix and keep the shape to allow for user's touch. In this application, we expect that the texture drawing work is performed by the user after fixing. So it is necessary to harden the surface does not change even when touched by the user.

Reset the shape

To reset the shape that has been created is an equivalent operation to return to the original flat state. Note that, this prototype does not have a capability to make the surface flat automatically. So the system only supports the user to make a remodel the surface flat using their hands by resetting the display pressure to atmospheric pressure.

In addition, the created shape can be easily captured and converted to 3D CAD data using the depth camera (Kinect) mounted for touch detection. However, some shapes created such as those with overhanged shape, can be not be fully scanned due to obstruction by the shape itself. In this case, additional Kinect camera can be used to capture generate model surface geometry while moving the camera around the model. In our current implementation, the capturing and converting functionality was implemented using the Microsoft Kinect SDK "Kinect Fussion". The captured model CAD can then regenerated using 3D printer, showing our system capability to be used as a fast simple model prototyping purpose.

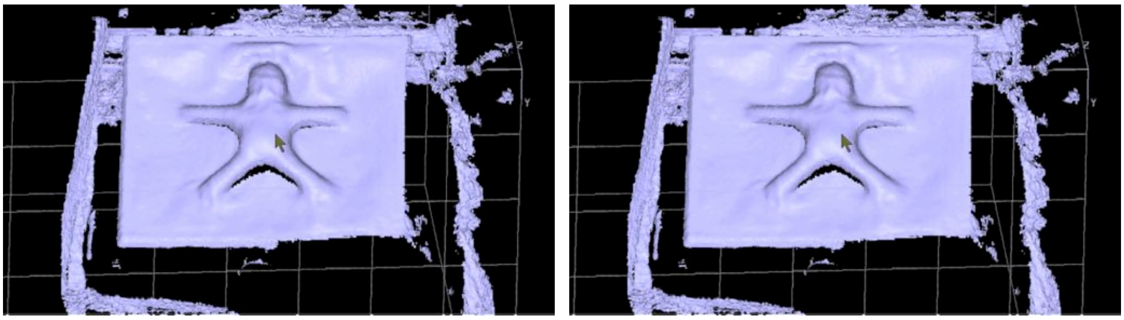

Figure 5.7: 3D CAD scan

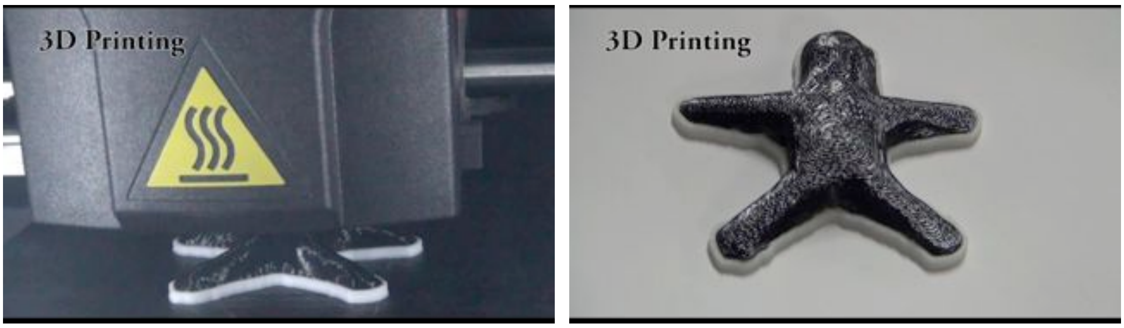

Figure 5.8: 3D printer output

This modeling application is also an example of a visual and tactile rich entertainment application as the user can perform modeling whilst experiencing various dynamic tactile feedback as the surface state transitions between soft and hard. Aside from the unique and artistic expression of our system, the system presents a simple reset transition, collapsing the shape and removing any traces by resetting the internal pressure to atmosphere.

5.2.3 Modeling support tool

Using a pre-prepared mold, a detailed 3D shape can be easily copied and formed. While in the soft state, user can place the molding tool on the desired location of the display. By activating the pump that is connected to the tool, the air between the mold and display surface will be vacuumed and the surface will be pulled into the mold shape (Figure 5.9). Hardening the display in this state will result in the mold shape being transferred and maintained on the surface.

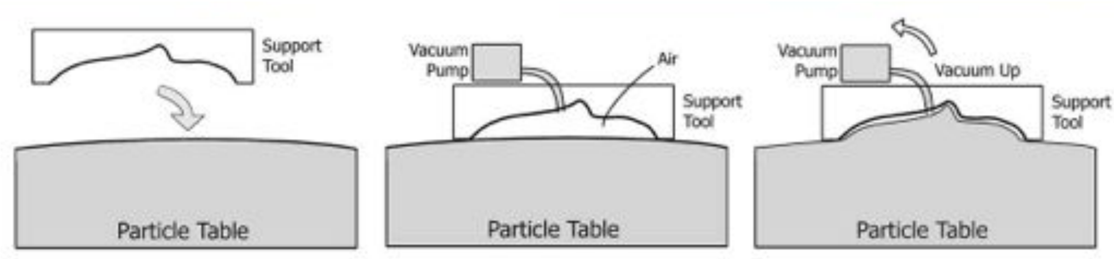

Figure 5.9: Configuration in appearance

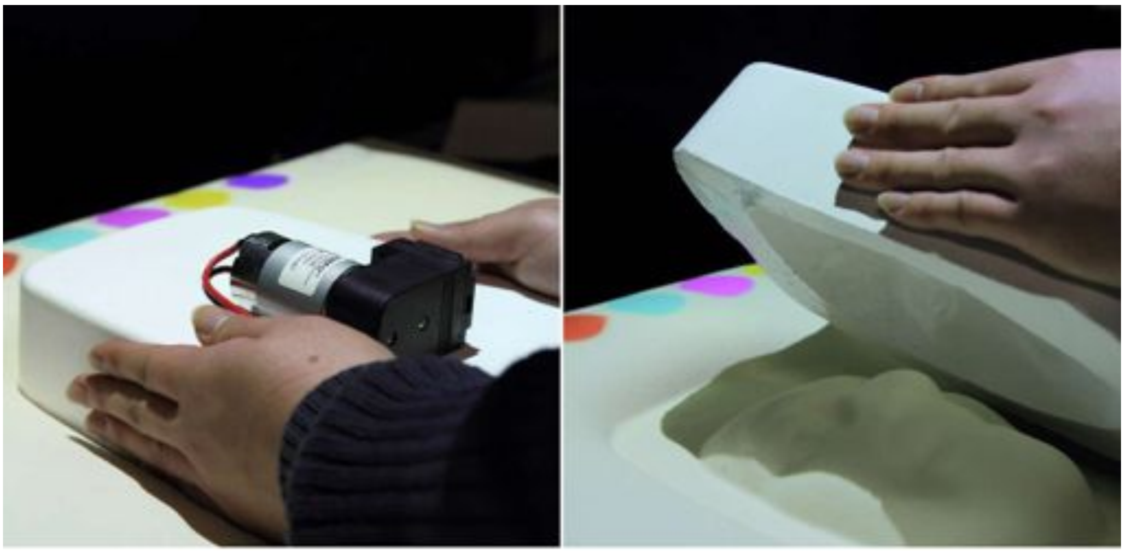

Figure 5.10: Configuration in appearance

5.3 Pen based input application

To supplement our modeling application, we also developed a paint application using dynamic stiffness control(Figure). This application has a 1cm thin particle layer installed upon a pen input device(Wacom Intuos4) which can detect pen input through the particle layer. In this application, the user can set stiffness of the display using a GUI slider on the display to make three-dimensional texture on the surface by hand. The user can manipulate tactile sensation felt through the pen whilst drawing to represent different types of brush. Furthermore, by drawing at a high input pressure, a pen trajectory is left as a three dimensional path on the surface. This trajectory can directly sensed by touch which implies possible applications for users with visual disabilities.

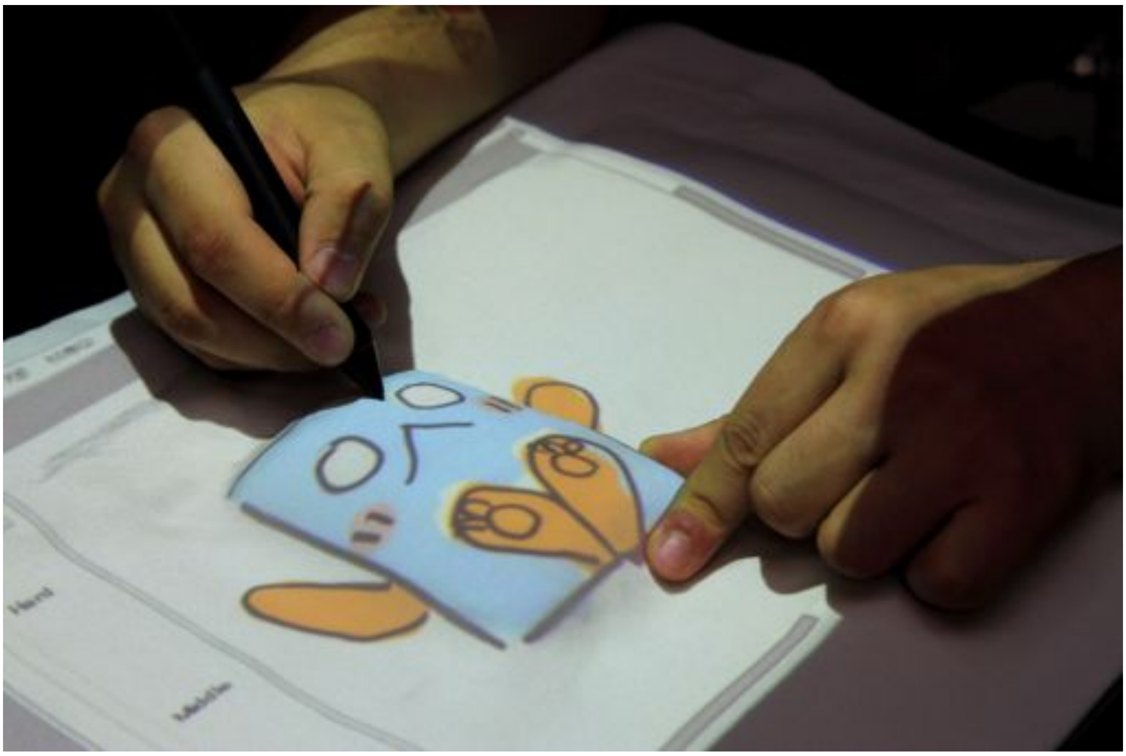

Figure 5.11: Configuration in appearance

Chapter 6

Particle display shape actuation

Though vacuum jamming is an effective way to control the surface stiffness properties, the jamming itself can do no external work on the surface material to enable shape deformation. Therefore, even though the user can fix or change the surface shape at freewill, the shape itself depend entirely on the user hand manipulation.

Recently, other researches that also have utilized vacuum jamming method on deformable interface have demonstrated how the self-actuated surface deformation is possible by combining it with another actuator e.g.: pressured cell and cylinder piston as presented by Hovermesh [21] and Haptic Jamming [33](Figure 6.1).

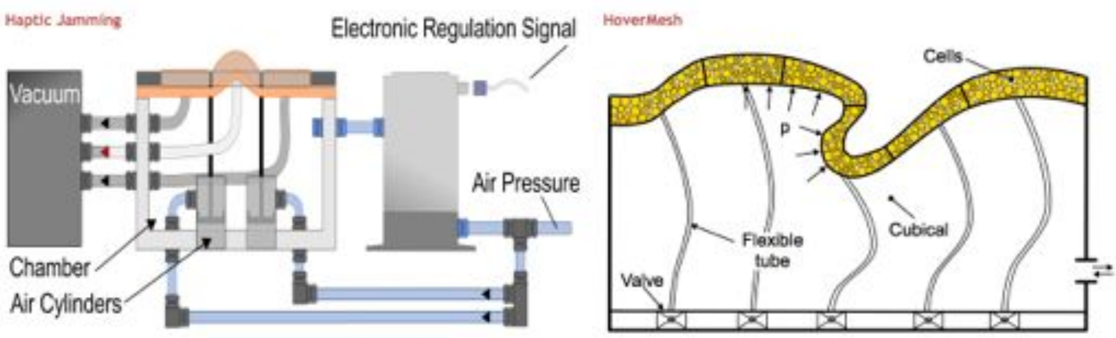

Figure 6.1: Left: HoverMesh pneumatic actuation, Right: Haptic Jamming piston actuation

Even though these presented methods have potential to accommodate shape deformation, they also has following problem:

1. System can become complex and hard to implement.

Because the shape actuation and stiffness control hardware are systematically different, the system can become complex and hard to implement.

2. Resolution degradation.
   One of the particle jamming superiority is the ability to represent a shape with high details. However, due to the design requiring surface to be separated into mesh structure, the shape expresiveness itself must be sacrificed.

3. Weak compatibility with vacuum jamming
   Because the actuators and stiffness control are systematically different, the control need to be perfectly synchronized e.g.: actuator motion when display is stiff might damage the display.

4. Softness change vs Surface change
   Based on the system design, the surface need to be hardened to change the shape. Therefore, when display is shaped, the softness can not be changed other than rigid state.

To overcome this problem, in this research we proposed a new display actuation method that allow both shape deformation and stiffness control using a pneumatic conveying particle transport technique called "LivingClay". Display geometries can be changed by transporting an amount of particles between display cells and the particle tank using a controlled air flows.(This method allow for a more simple and effective way to change surface shape. This method also have high compatibility with jamming method because using same line of pneumatic actuation.)

6.1 Particle transport using pneumatic conveying

Particle transport using pneumatic conveying technique has been a common method used in the agriculture (flour, sugar), mine and chemical industry. Currently, there also other techniques such as belt conveyors, screw conveyors, vibrating conveyors, drag conveyors to carry and transport granular material. However, compared to other techniques pneumatic conveying has the following 3 basic advantages [2] :

1. First, pneumatic systems are relatively economical to install and operate
2. Second, pneumatic systems are totally enclosed and if required can operate entirely without moving parts coming into contact with the conveyed material.
3. Third, they are flexible in terms of rerouting and expansion. A pneumatic system can convey a product at any place a pipe line can run.

However, pneumatic conveying also has some limitation which is the materials transported required to be lightweight and small. Based on [2] the particles can be can be used for pneumatic conveying ranging from fine powders to pellets and bulk densities of 16 to 3200 kg/m^3. In this research, we use polystyrene particle with 1mm in diameter and densities of 1000kg/m^3.

There are several methods of transporting materials using pneumatic conveying. In general, they seem to fall into three main categories: dilute phase, dense phase, and air conveying[2]. In this research, we will focus on dilute phase methods which is the most common used method of transporting materials.

Dilute phase conveying is the process of pushing or pulling air-suspended materials from one location to another by maintaining a sufficient airstream velocity(fig. 6.2).This process uses a relatively large amount of air to convey a relatively small amount of material and at lower pressures than dense phase systems. The material is transported at high velocities through the system while being suspended in air.

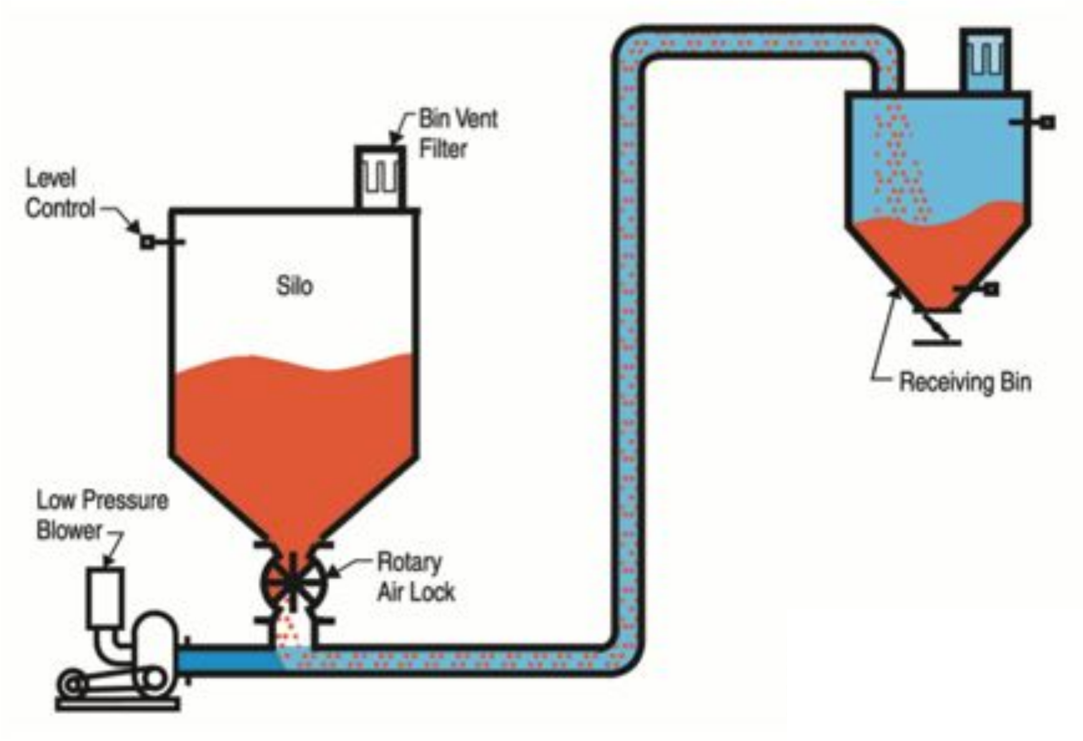

Figure 6.2: Dilute phase pneumatic conveying

It is often referred to as suspension flow because the particles are held in suspension in the air as they are blown or sucked through the pipeline. To keep the material in suspension, it is necessary to maintain a minimum conveying air velocity that, for most materials, is of the order of 2500 to 6000 fpm.

Dilute phase system is characterized by:

- High velocity conveying 3,200 to 8,000 feet per minute
- Operating pressures in range of 5-12 PSIG (positive) or negative pressures of 4- 12 Hg
- High air to solids loading ratios (¿ 2.0)

Material velocity In dilute phase conveying, with particles in suspension in the air, the mechanism of conveying is one of drag force. The velocity of the particles, therefore, will be lower than that of the conveying air. It is a difficult and complex process to measure material velocity, and apart from research purposes, particle velocity is rarely measured. It is generally only the velocity of the air that is ever referred to in pneumatic conveying.

- In a horizontal pipeline the velocity of the particles will typically be about 80% of that of the air. This is usually expressed in terms of a slip ratio, defined in terms of the velocity of the particles divided by the velocity of the air transporting the particles, and in this case it would be 0.8.
- In vertically upward flow in a pipeline a typical value of the slip ratio will be about 0.7.

Air Volume vs Velocity Relationship For any given material, there is a minimum transport velocity required to convey the material, therefore, the airflow rate (volume) will depend on the size of the pipe. The airflow - velocity relationship is governed by equation:

$$v = V/(\rho * A) \tag{6.1}$$

where

- V = volumetric air flow rate in ft3/min (cfm)
- ρ = density of air (lbs/ft3)
- A = conveying pipe area ft2
- v = conveying velocity in ft/min (fpm)

Even though this particle pneumatic conveying method has been applied in various field of engineering, the adoption of this technique for user interface has been yet to be explored.

6.1.1 Time vs volume change

In this research, we use the pneumatic conveying method to transport and control the volume of particle inside the display. Therefore to allow a smooth and precise volume control, we conducted an experiment to investigate the consistency of controlled particle volume while changing the pneumatic actuation time.

In this experiment, we connected 2 jar(jar A and jar B) using a tube with internal diameter of 10mm. Next, we filled jar A with 1mm polystyrene particles until 80% of the jar volume. Then, using dilute phase conveying method, air from pneumatic pump blown into the jar A to jar B and back into the pump. As the air circulated inside the closed system, particles material also blown and transported from jar A to jar B. In this experiment we use a pneumatic pump with flow rate of 40L/min, and the measured pressure inside the system is kept at 0kPa. Figure 6.3 show the configuration of the experiment.

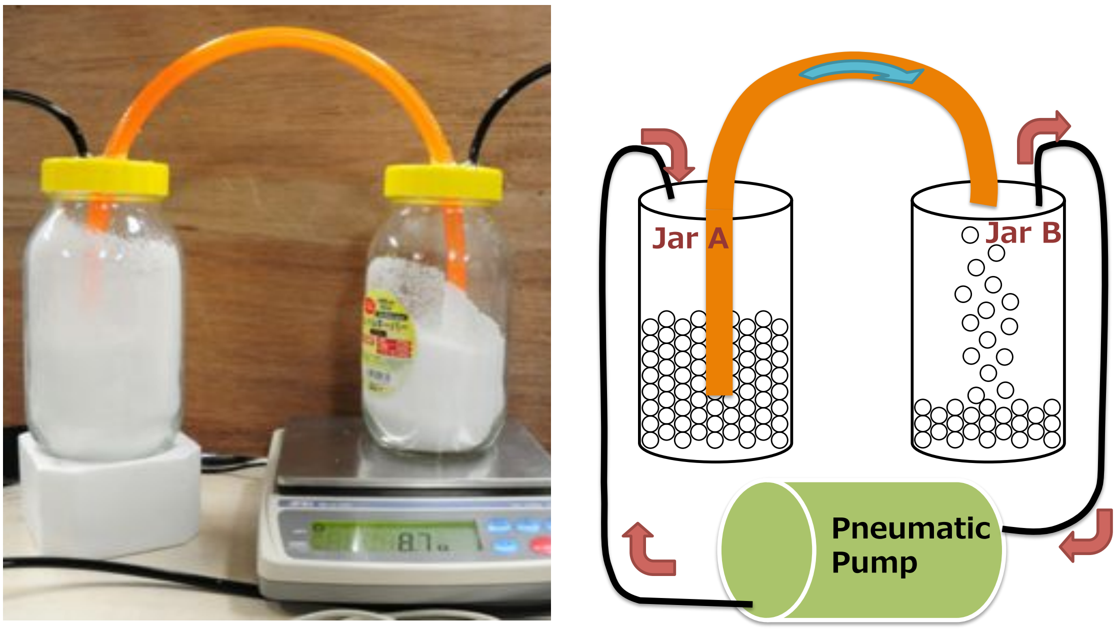

Figure 6.3: Time vs volume change experiment

After the pump activated for 100ms, then we measured the transported particle weight at jar B using a digital weight scale. After measured weight is recorded, we put back the particle from jar B into jar A. We repeated the measurement 20 times and record the weight data. We also changed the activation time in step of 100ms from 100ms to 500ms, and in step of 200ms from 600ms to 1600ms and repeated the measurement at each step. The volume change is then calculated using polystyrene particles density of $32\text{g}/\text{mm}^3$. Figure 6.4 shows the results of the experiment.

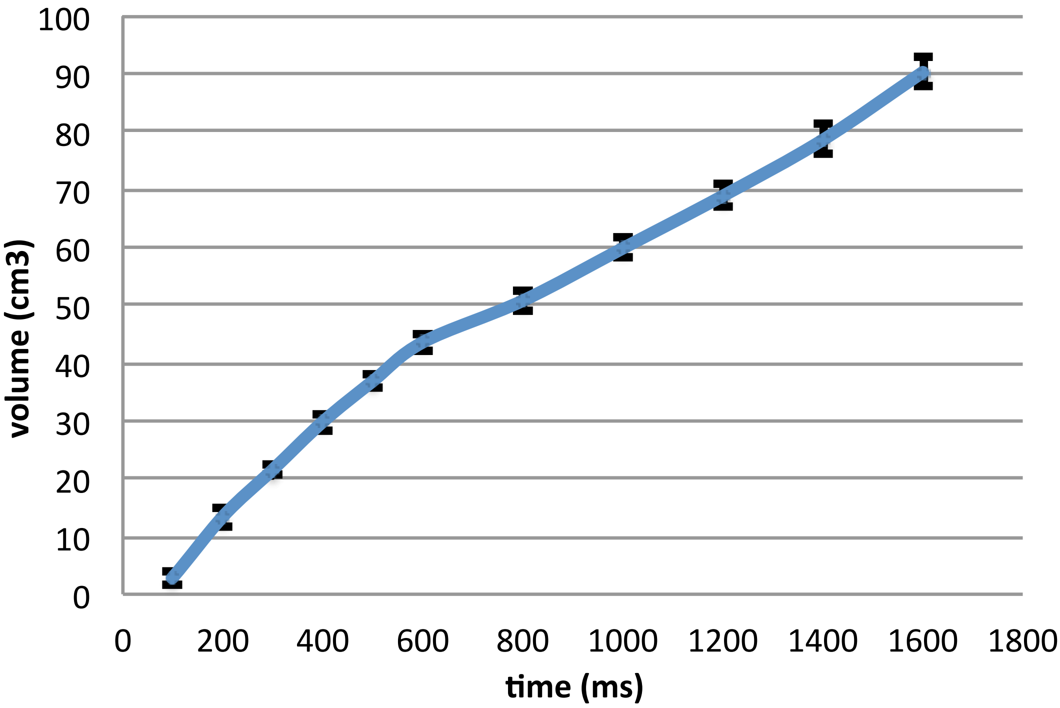

Figure 6.4: Time vs volume change relation

Based on the result, the following observation can be seen.

- The particle volume transported is consistent with average standard deviation of 1.7 cm^3.
- The volume is increased in accordance with the in raise in pump actuation time, close to linear relation.

This result proof that the volume can be controlled specifically by changin the actuation time respectively.

6.1.2 Initial volume vs volume change

Based on the observation at the Time vs volume experiment, we also found that the initial volume at jar A also affect the volume of transported particles. Therefore, we also conducted an experiment to investigate the relation of initial volume with the controlled volume change. In this experiment, we use the same configuration as the time vs volume measurement. However, instead of the pump actuation time, here we change the initial particle volume relevant to jar volume (maximum 20g of particle) from 4% up to 100% with step of 2% . Then we conducted the measurement at 2 fixed pump actuation time (200ms and 500ms) and record the weight data at each measurement. Figure 6.5 shows the results of the experiment.

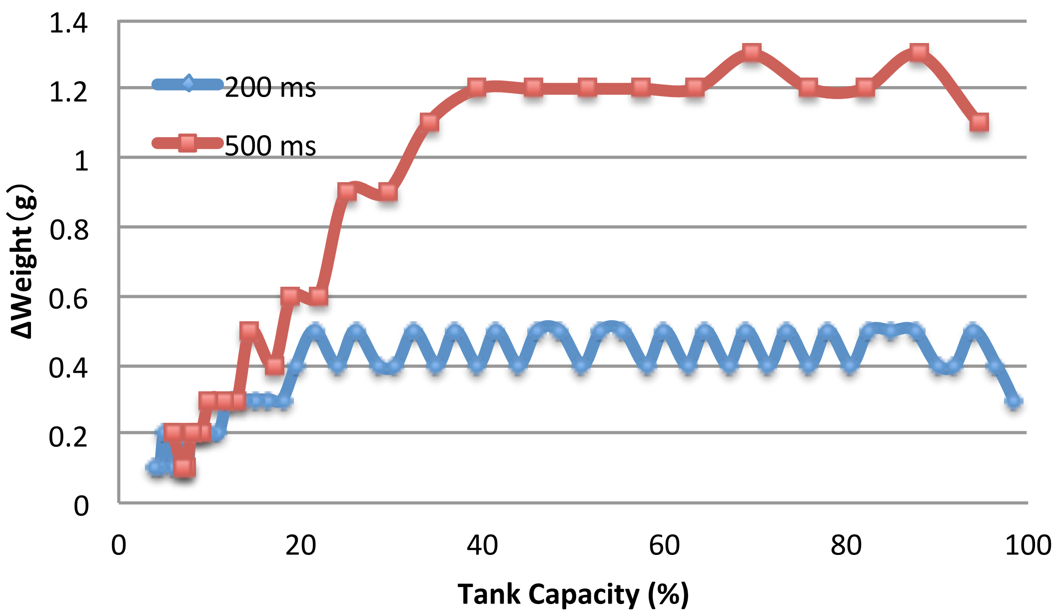

Figure 6.5: Initial volume vs volume change relation

Based on this result, we conclude that for reliable and stabile volume control, the initial tank volume need to be kept at about 40% to 80% of the tank.

6.2 Hardware configuration

Figure 6.6 show the design of our display actuator.

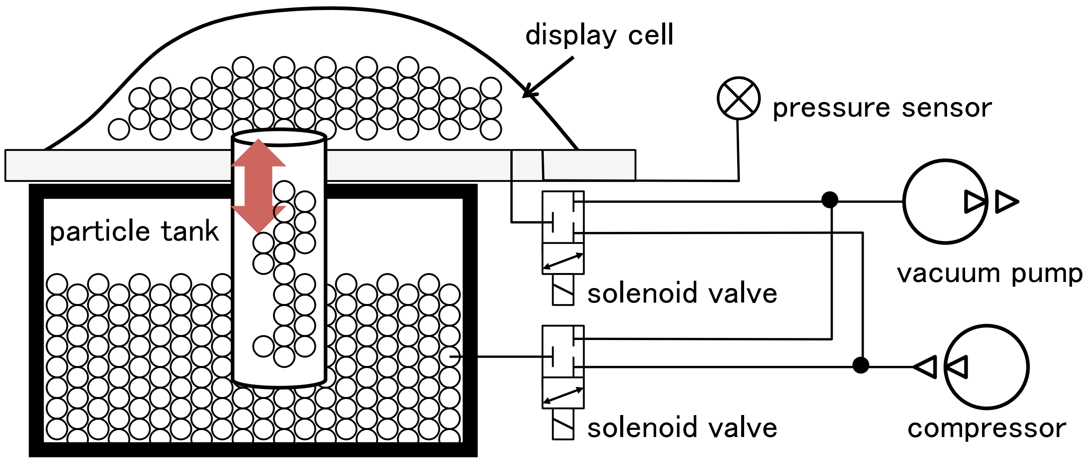

Figure 6.6: System configuration

Our hardware configuration generally consist of 2 unit: display unit and pneumatic unit. We also can add projector and camera unit to allow graphical input and output as we did in ClaytricSurface.

6.2.1 Particle cell

The display unit consists of a hollow layer of flexible cell and a particle tank under it. The display cell and particle tank are linked with a 10mm inner-diameter tube. The particle tank is filled with an amount of polystyrene particle up to 80% of its volume. Using the pneumatic conveying this particle can then be transported into the display cell vice versa. For the first prototype we created the display cell with size of 150x 150 mm with maximum height of 50mm. For the particle tank, we used a cylinder with diameter of 150 mm and height of 180mm. Based on a trial, we found that the appropriate volume ratio between particle tank and display cell is respectively 3:1.

6.2.2 Pneumatic unit

The pneumatic unit consists of:

- Pneumatic vacuum pump.
  We use Medo VP0625 a linear motor piston pump that can be used as a source for both vacuum (negative pressure) and compression (positive pressure). The pump speed is 40L/min and maximum vacuum level attainment is -33.3kPa.

- Solenoid valve.
  Both the cell and particle tank are connected to a 3 ports solenoid valve able to select a connection between positive or negative air flow to vacuum pump. Here we use CKD 3PB2 3 ports solenoid valve.

- Pressure sensor.
  We use Fujikura XFPN-03PGVR pneumatic pressure sensor that can measure relative pressure from atmospheric (0kPa) up to -24.5kPa.

- Micro Controller.
  We use Arduino Uno that has A/D conversion resolution of 10 bit and clock speed of 16MHz.

Each of the pressure controller are linked with a 4mm inner-diameter tube.

6.3 Particle volume control

In this research, we use pneumatic conveying method to control the particle volume inside the display. Generally, the control can be divided into : raising volume, and shringking volume.

6.3.1 Raising volume

The display volume is raised by transporting an amount of particles from particles tank into the display cell. First, an air flow from particle tank into display cell is created by connecting the particle tank with compression line and the display cell with vacuum line through the operation of solenoid valve. The created airstream then become a suspension, carries particles through connecting tube into the upper display cell, raising the particles volume inside display cell (figure 6.7). Specific surface volume can be controlled by altering the actuation time of the air flow.

To allow a smooth particles transports, the pressure need to be kept at positive compressed pressure (0.1 0.5kPa). Therefore, the display cell will be inflated, creating opening space to be filled with particles. Conversely, if pressure kept at negative vacuum pressure, the display cell will be sucked, blocking the particles from entering the cell.

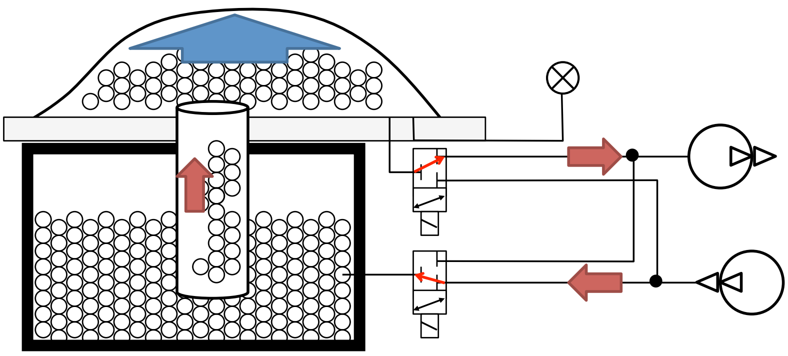

Figure 6.7: Volume raise proccedure

6.3.2 Shrinking volume

We identify two ways to shrinking the display volume.

1. Create a reversing air flow By creating an air flow from display cell into particle tank (while keeping a positive air pressure), will allow the particles to blown back into the tank below, reducing the display volume(figure 6.8left). In contrast with raising volume control, the particle tank is connected into compression line while display cell is connected into vacuum line.

2. Sucking particles with vacuum Different from the raising volume control, the particle inside the display can be sucked deliberately into particle tank by connecting the tank with vacuum line while sealing the connection into display cell(figure 6.8right). In this case, the pressure inside is kept at negative pressure. This method reducing the volume slower than the reverse air method, but allow for a more specific volume control.

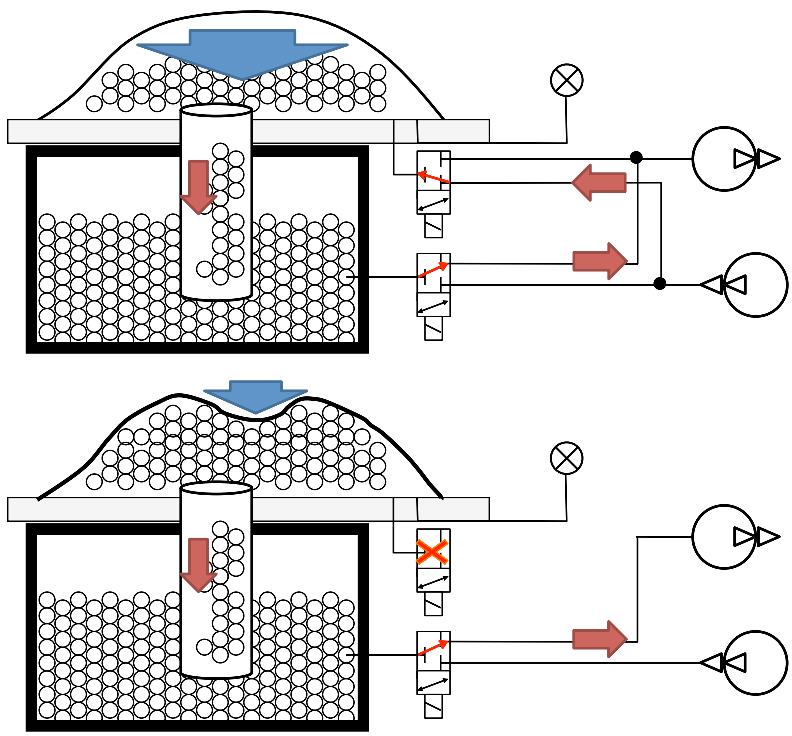

Figure 6.8: Volume shrink proccedure

6.3.3 Stiffness control

In this system, the particle-filled display softness can also be controlled using vacuum jamming technique. First, the air connection into particle tank need to be sealed, next by connecting vacuum line into the display cell, the pressure can be controlled using the same method as described in ClaytricSurface(figure 6.9).

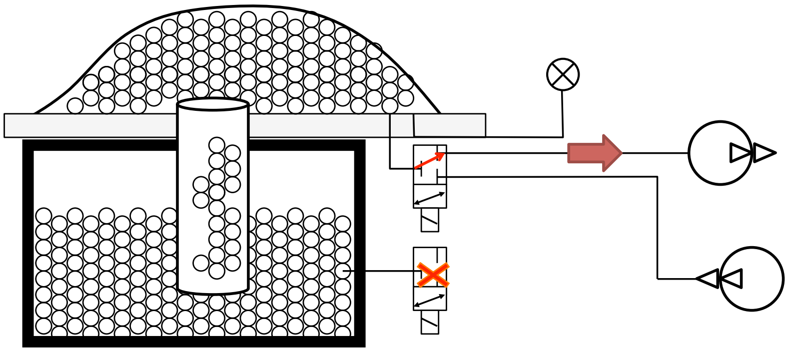

Figure 6.9: Stiffness control proccedure

6.4 Display actuation state

In this system, the display can be actuated into 3 state: flat surface, convex surface filled with particles, and convex surface inflated with air. In addition, when display is filled with particles, the softness also can be controlled using the vacuum jamming technique.

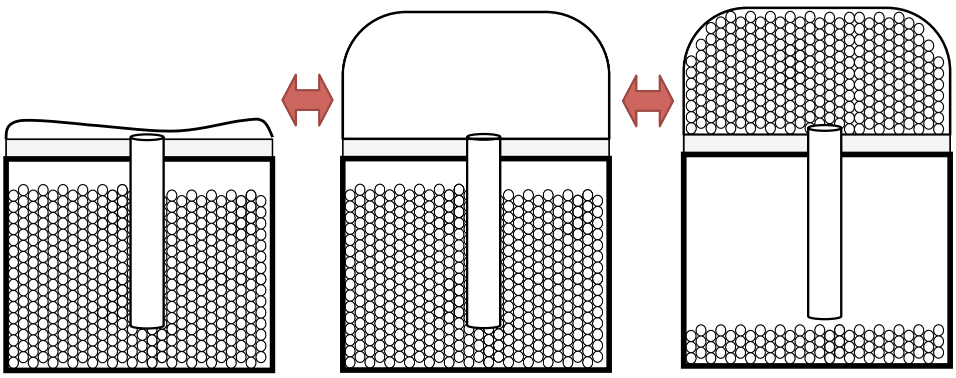

Figure 6.10: LivingClay display state: Flat, Convex particles filled, Convex

Flat surface

To create a flat surface, first the display cell required to be emptied and all the particles is stored inside the particle tank. Then, by applying vacuum through the display cell connection, the thin flexible surface material will fit the display base shape and create a flat rigid surface (figure 6.10 left).

Convex air-inflated surface

The convex air-inflated surface can be created by applying compressed air into the display when display is flat or when the display filled with particles(figure 6.10 right). In this state, due to the surface flexible material, the shape is deformable when force applied. However, the shape will turn back into convex when the deforming force is released. When touched, the surface has a balloon like bouncy tactual feel.

Convex particles-filled surface

The convex particles-filled surface can be created by conveying an amount of particles from particles tank into the display cell using the pneumatic conveying method(figure 6.10 center). Here, because the particle transfer line is quite small, applied external force into the cell will cause the particle to be jammed at the tube entrance. Therefore the particles will stay from returning to the particle tank even when the user manipulating the surface. In addition, similar to ClaytricSurface, in this state the shape can be deformed by the user hand and the softness also can be controlled at freewill.

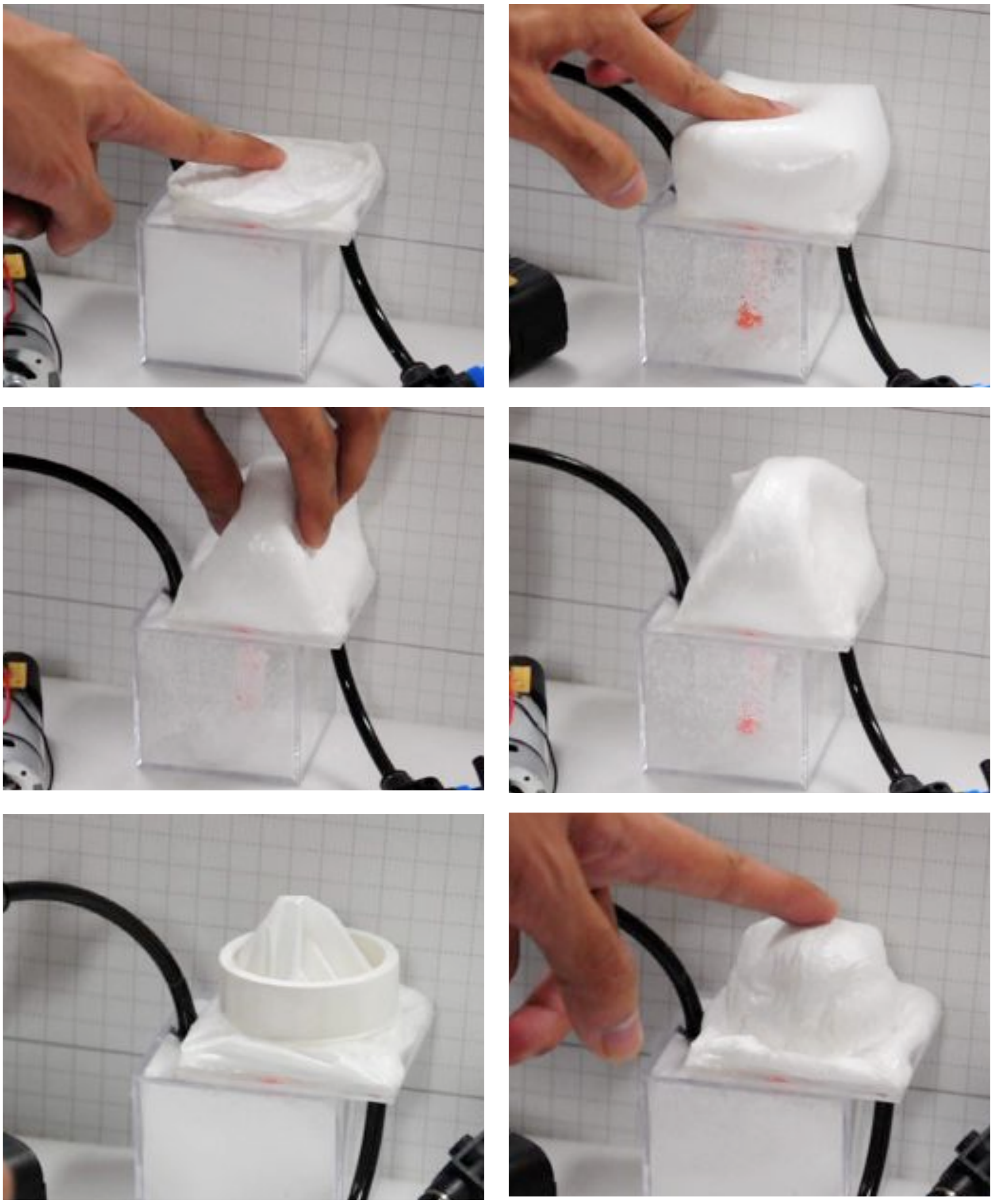

Figure 6.11: Actual display actuation

Chapter 7

Interactive surface with controllable softness and shape

We identify our vision of display as follow:

1. Surface softness and flexibility can be changed dynamically.
2. Both self-actuated shape change and also deformation by user direct input.
3. High resolution (detailed shape).
4. Low-cost and efficient.

However, with our current technology, it is nearly impossible to realize a display that fulfill all these requirement. Therefore, we plan to implement some specialized display that able to attained some of the requirement to allow a particular application. Here, we propose the design of interactive surface with controllable softness and shape change.

7.1 Array actuated display

On previous chapter, we describe how a pneumatic conveying actuation (LivingClay) can allow controlled volume change. However, the geometry that can be represented using one actuation is very limited to a convex and flat shape. Here, we propose an implementation of array arranged LivingClay actuation which is able to both render and animate 2.5 dimensional shapes and changing the surface softness.

7.1.1 System configuration

Figure 7.1 show the configuration of the display system.

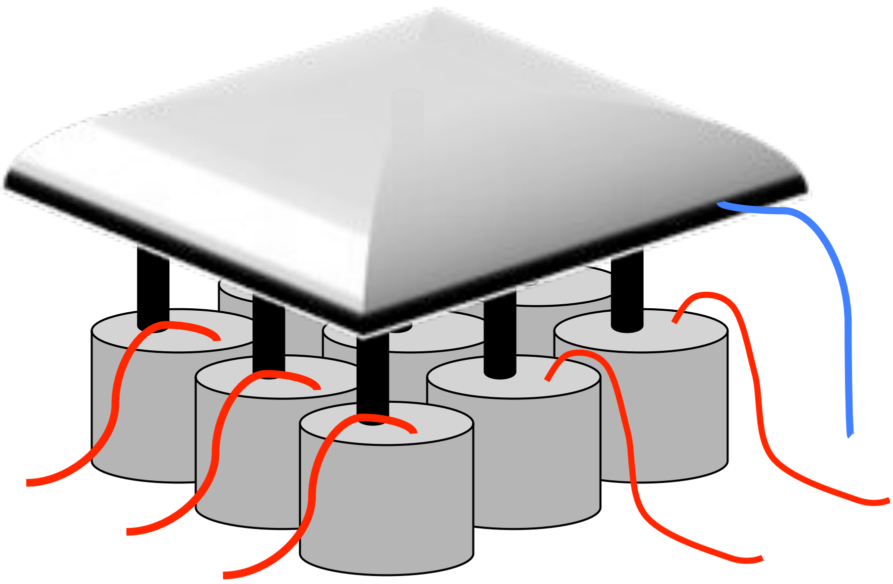

Figure 7.1: System outline

In general, the system consist of :

Display cell. The display unit consists of a hollow layer of flexible cell with multiple particle tanks arranged in matrix linked with 10mm inner-diameter tube.

Pneumatic control. The display cell is connected to 2 solenoid valve, able to select a connection between vacuum, compressed air, or ambient air. Each of the particle tanks also connected to one solenoid valve and another one before connection to blower, allow for select a connection between vacuum, compressed air, or sealed.

Figure 7.2 show the configuration of system hardware viewed from side.

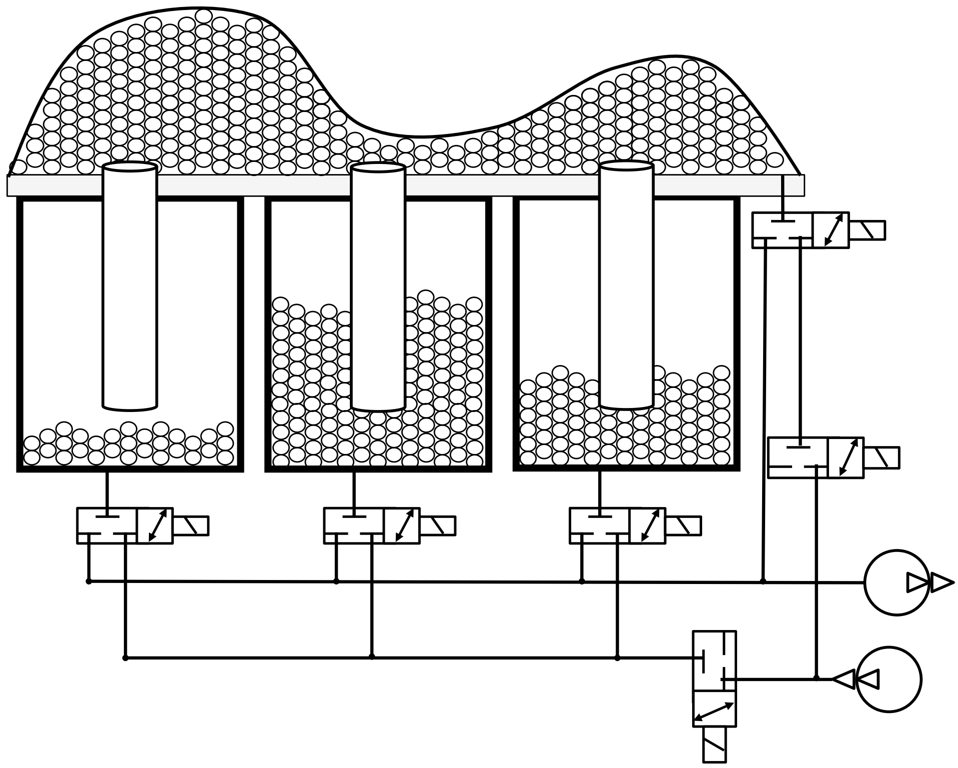

Figure 7.2: Hardware configuration

7.1.2 Display actuation state

In this system, generally the display can be actuated into 3 state: flat empty surface, convex particles-filled surface, and geometry rendered surface. Depending on the state, we define the display purpose as:

1. Changeable softness display. When the display is fully filled with particle, the surface can be used like ClaytricSurface display e.g.: modeling application, etc.

2. Approximately rendered shape display. Using the LivingClay actuation, a selected area in the display can be shrink, rendering some low resolution shape.

3. Traditional flat surface. When the surface is empty of particle, the surface can be functioned as a normal flat surface.

In this system, the actuation state is changed in one directional flow, starting with convex particles-filled surface(figure 7.3 upper), next to shaped surface(figure 7.3 bottom left), then to flat empty surface(figure 7.3 bottom right), and back to convex ones.

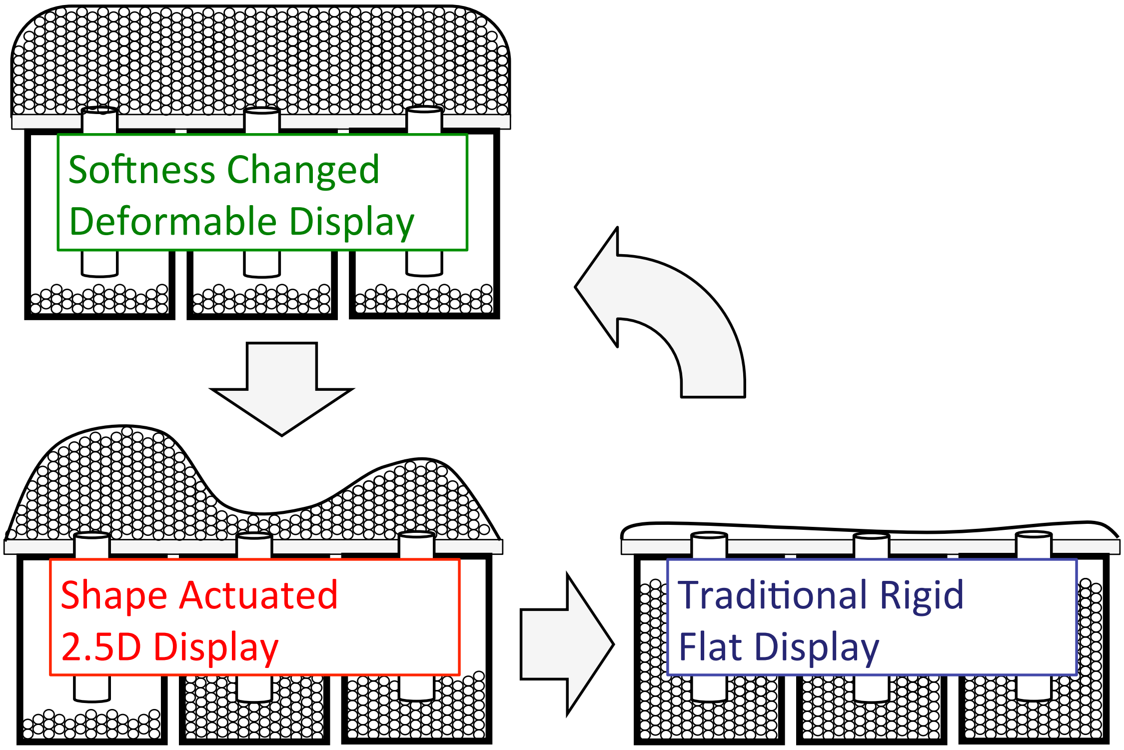

Figure 7.3: Display actuation state

7.1.3 Implementation

To demonstrate the usability of our design, we implemented a prototype system with 2x3 actuator attached. The display size is 160x120mm, maximum height of 35mm, and the surface area for each actuator is 50x50mm. Figure 7.4 show our prototype display.

For particle tank, we use 160mm length and 50mm diameter PVC pipe with pressure durability up to 202kPa. For the pneumatic control, we use 11 solenoid valve (6 connected to each particle tank, 1 into display cell, and 4 for pressure

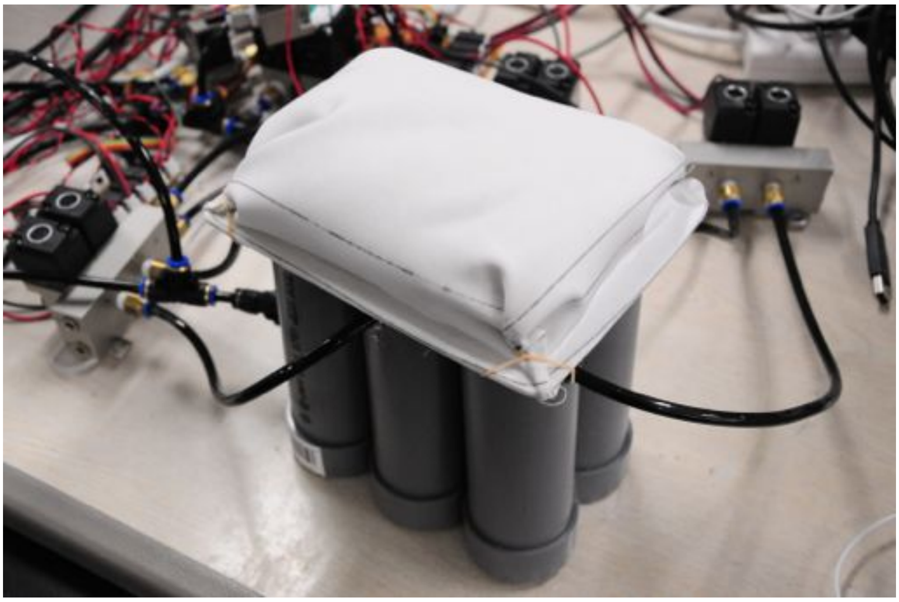

Figure 7.4: Prototype display appearence

control), a pressure sensor, and a vacuum pneumatic pump (with inlet and outlet). Figure 7.5 show the implemented hardware system.

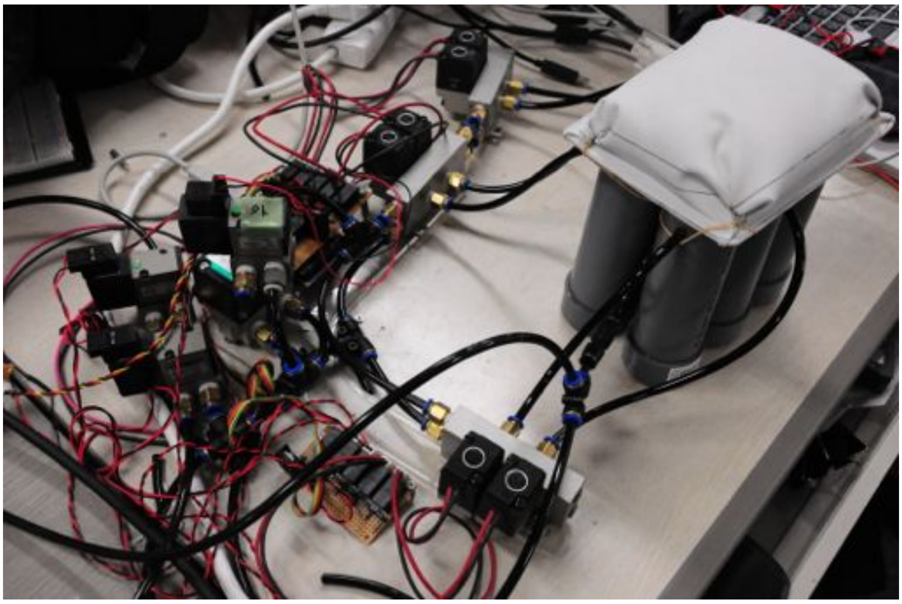

Figure 7.5: System hardware appearance

7.1.4 Shape actuation control

In this implementation, generally the shape actuation is similar to "LivingClay" actuation method. First, the surface initialized as a flat particle-filled surface kept at hardened state(Figure 7.6 left). Next, using vacuum shrinking method (as described in 6.3.2), connection to display cell is sealed, and vacuum line connection applied to the selected particle tank. This will resulting in a specific area above the selected particle tank to be shrink (Figure 7.6 right).

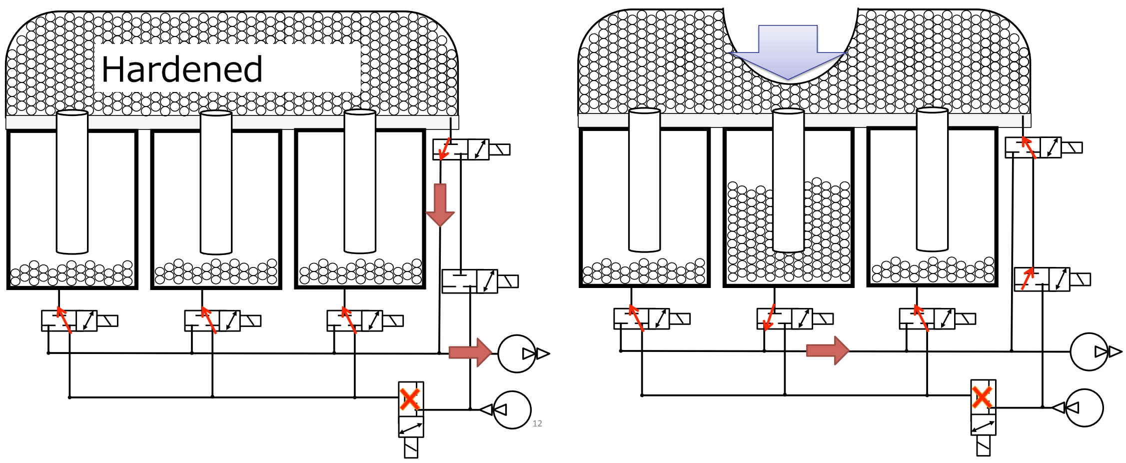

Figure 7.6: Shape shrinking actuation

We found that the particle collapse only in vertical direction when the surface kept at hardened state first. It can be considered that due to the vacuumed state, the ambient air pressure is stressing the display mostly from the upper side(because the top surface created from flexible material). This pressing force combined with the vacuum from particle tank under, resulting in straight forward shrink down movement (figure. 7.7 left).

Also, as the cell surface is shrinking down and contacting the linking tube, the surface material is getting sucked, blocking the tube from sucking particle any further (fig 7.7 right).

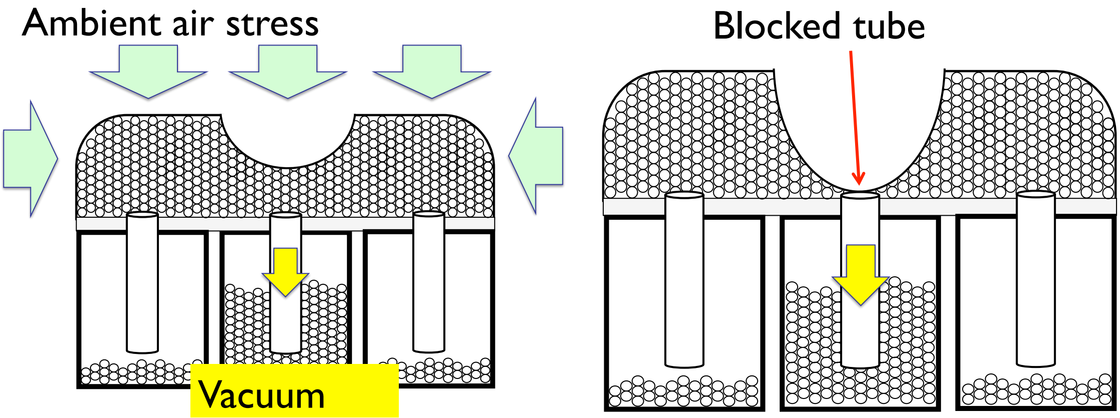

Figure 7.7: Left: straight shrink, Right: Blocked tube

7.1.5 Shape and softness copy application

To demonstrate the capability of this system, first we propose an application of shape and softness approximation copy application.

In this application, first the user can place a physical object at the top of the surface. Then, using Kinect camera mounted above the surface with background subtraction method, the object surface geometry can be captured.

Next, the user need to press the object at certain force using their hand. At this time, the monitored pressure change by pressure sensor value can be used to calculate the surface negative deformation. Using this pressure change data, system can then approximately determine the object stiffness level (with same pressing force, soft object deforming the surface less).

Next, the display can generate the approximation copy (adjusted to display resolution) of the object geometry and the approximated softness using stiffness control. For final procedure, user can then deform the shape accordingly, adjusting the shape and adding the detail.

Figure 7.8 show the outline of the application.

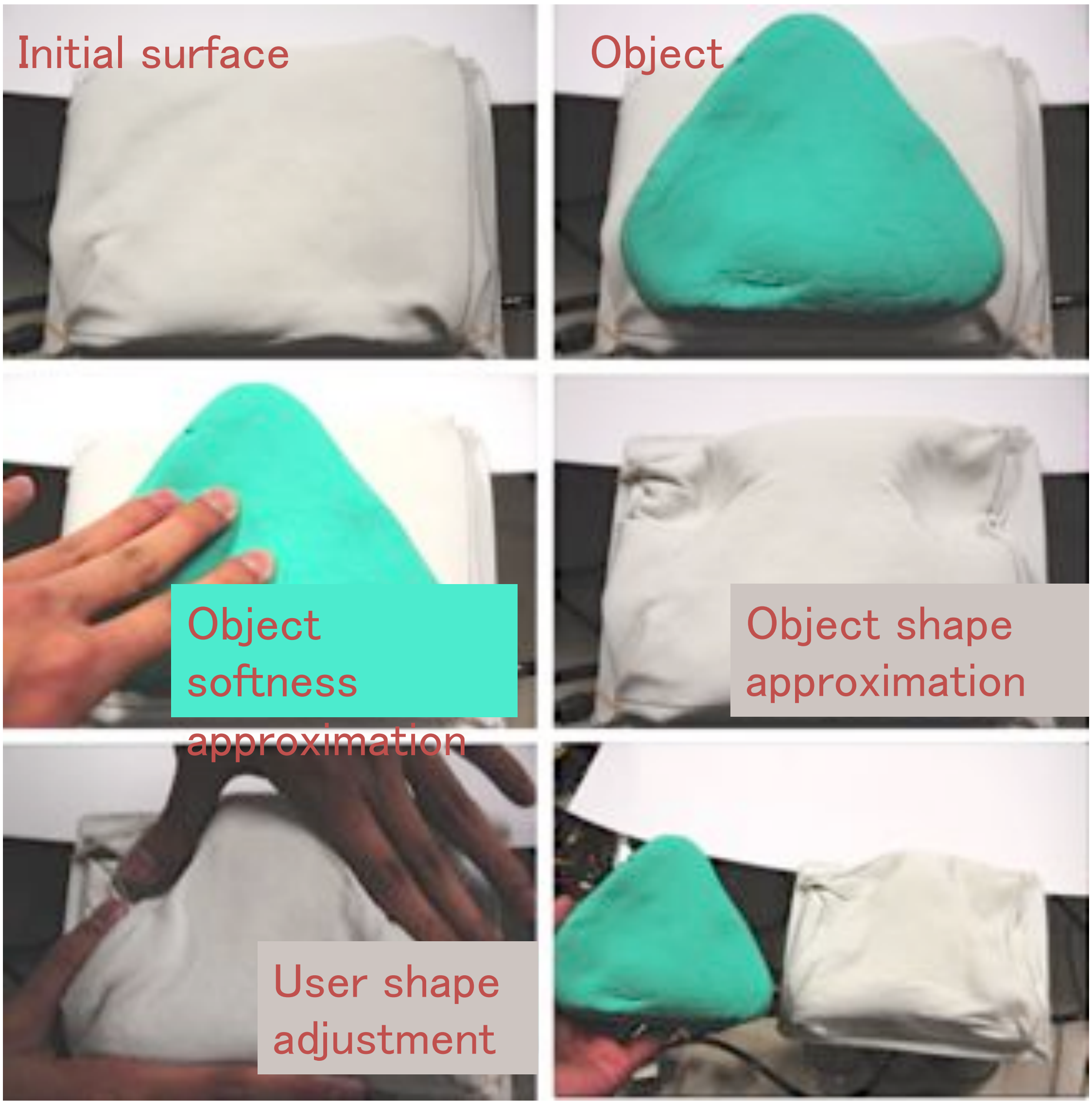

Figure 7.8: Shape and softness copy application

7.1.6 2D to 3D paint application

The purpose of this prototype application is for entertainment use, allowing the user to experiment with possibilities of a physical 3D shape generation from a mere 2D painted image.

In this application, when surface is flat and filled with particles, the user can draw a texture on display surface. The system then detect the drawn 2D shape and generate a 3D model based on the 2D shape and color. Figure 7.8 show the outline of the application.

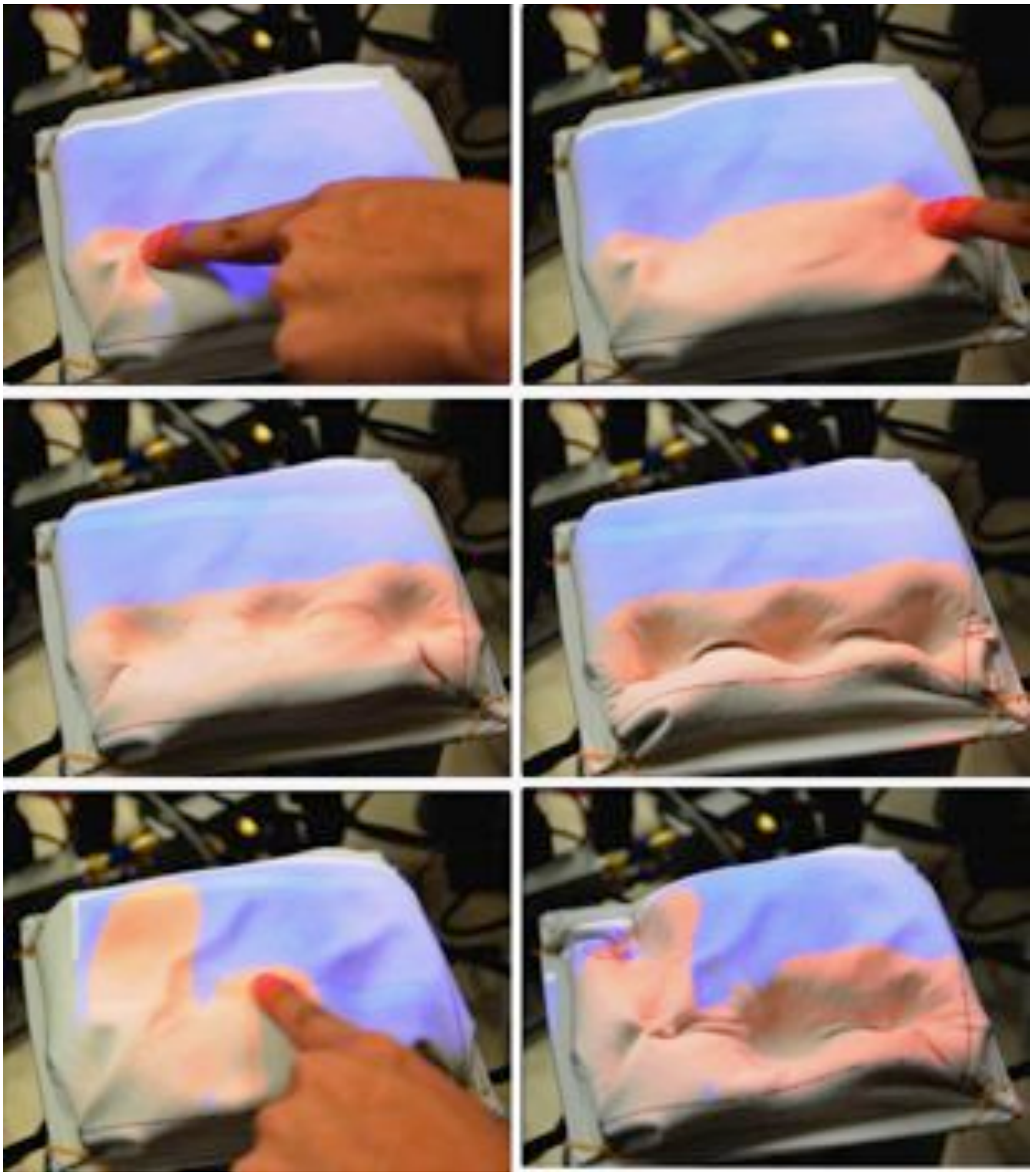

Figure 7.9: 2D to 3D paint application

7.2 Multiplexed mesh display

One of our research interest is to achieve a high resolution shape display with low-cost implementation. Here we propose an effective multiplexed grid air flow connection to control a matrix configured multi-cell display.

Compared to previously described self-actuated shape display (7.1), this system biggest characteristics is the reduction in the usage of solenoid valve while maintain the ability to control specific cell shape deformation. In addition, the display can be manufactured in separated module and then joined into a bigger resolution, making for a great scalability.

7.2.1 System configuration

In this system, a separated display cell arranged in matrix configuration. Each display cell is connected in vertical line while the particle tank is connected on the horizontal line(fig. 7.10).

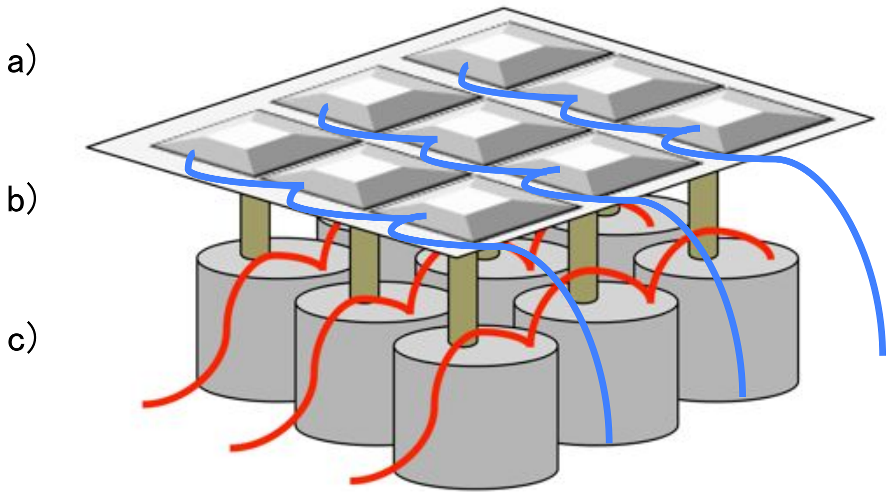

Figure 7.10: System design of array display: a) surface cell, b) transfer tube, c) particle tank

Different from previously described (7.1) system, because the display cell and particle tank connected in multiplexed grid, each particle tank not required to be connected to a solenoid valve. Instead, the solenoid valve only need to be connected into the edge of each display cell and the edge of each particle tank.

In example of a squared matrix arranged display, f(n) is the minimum required solenoid valve, and the matrix size is n x n pixels. In case of (7.1)system, the sequence can be defined as

$$f(n) = n^2 + 3 \tag{7.1}$$

while, for this multiplexed channeled system the sequence is

$$f(n) = 2 * n + 2 \tag{7.2}$$

Both of the cell line and particle tank line is then connected to solenoid valve at the end of line, able to select a connection between vacuum, compressed air, or ambient air. Figure 7.11 show the hardware system configuration.

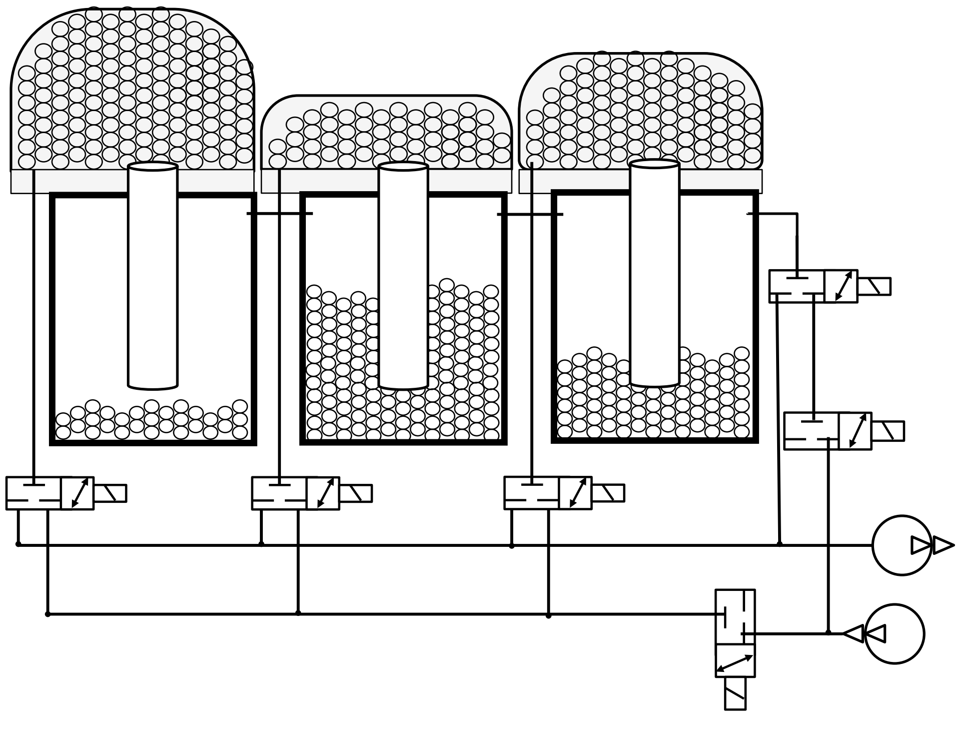

Figure 7.11: System hardware configuration

7.2.2 Implementation

To demonstrate the usability of our design, we implemented a prototype system with 3x3 matrix module. Each module has the size of 30x30mm and maximum height of 30mm. It then attached to a particle tank with diameter of 5mm and length of 200mm made of PVC pipe. Lastly, the module surface is adjoined together using tape to allow a continuous shape. Figure 7.12 show our prototype display in appearance.

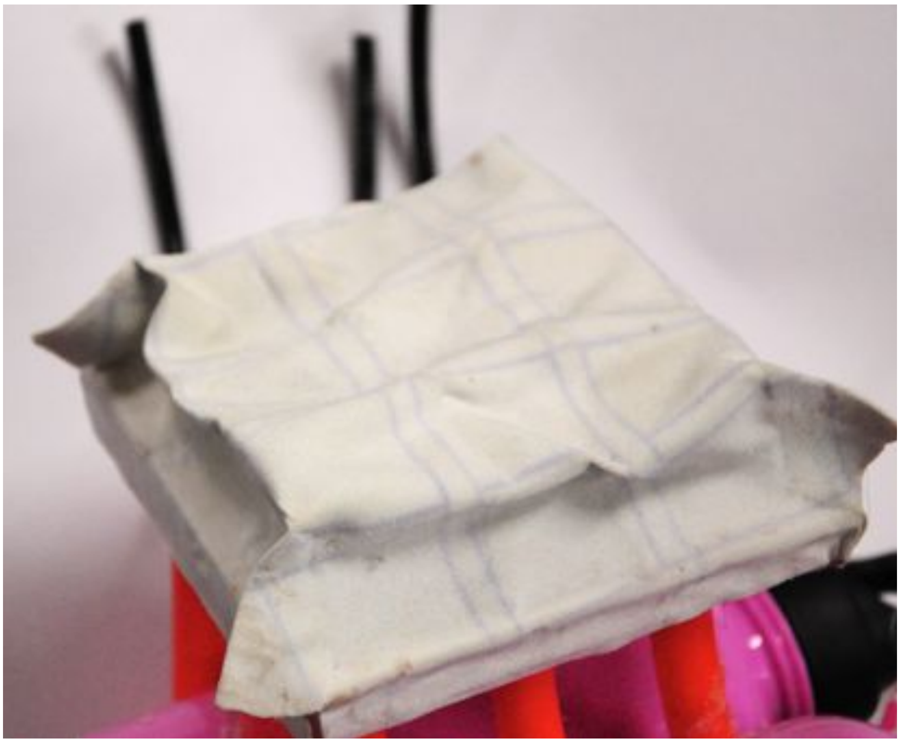

Figure 7.12: Prototype display system

7.2.3 Shape actuation control

In this system, to actuate a specific mesh of the display, special procedure of valve control is needed. Here we describe an actuation procedure in example of 3x3 mesh arrangement.

To raise a single cell in the middle of the matrix (figure 7.13 upper left), first, all the mesh other than the middle require to be jammed. This achieved by a applying a vacuum line into both the particle tank line and display cell line while applying compression line into the middle mesh. Resulting the middle mesh is inflated with air (figure 7.13 upper right). Next, while keeping the other mesh jammed, compression line is applied into the middle particle tank line and ambient air line into the middle cell line. This will resulting an air stream through middle particle tank to above cell, raising the display volume (figure 7.13 bottom left).

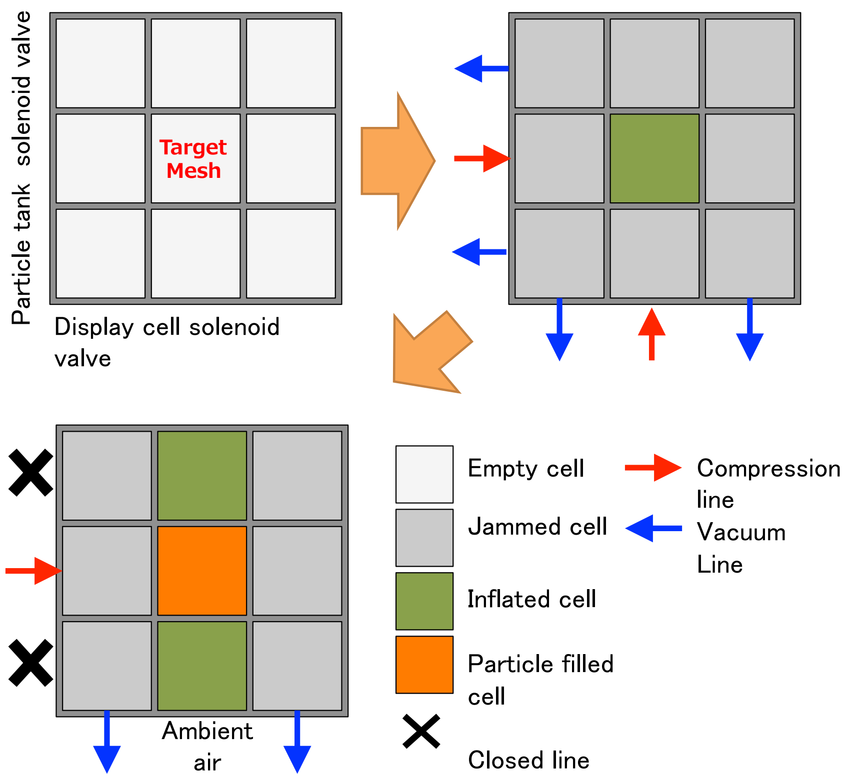

Figure 7.13: Cell raising procedure

Actually, air stream are also flowing at the surroundings mesh. However, due to the mesh jammed state, the particle flow into the display cell is blocked, resulting particle flow only at the middle mesh.

To shrinking the mesh is a more straightforward process. First, all the other mesh is also jammed, then applying compression line into the middle cell column and ambient air into the middle tank row(figure 7.14). . Apart from localized actuation, this system can also create a localized stiffness change. Similar to the

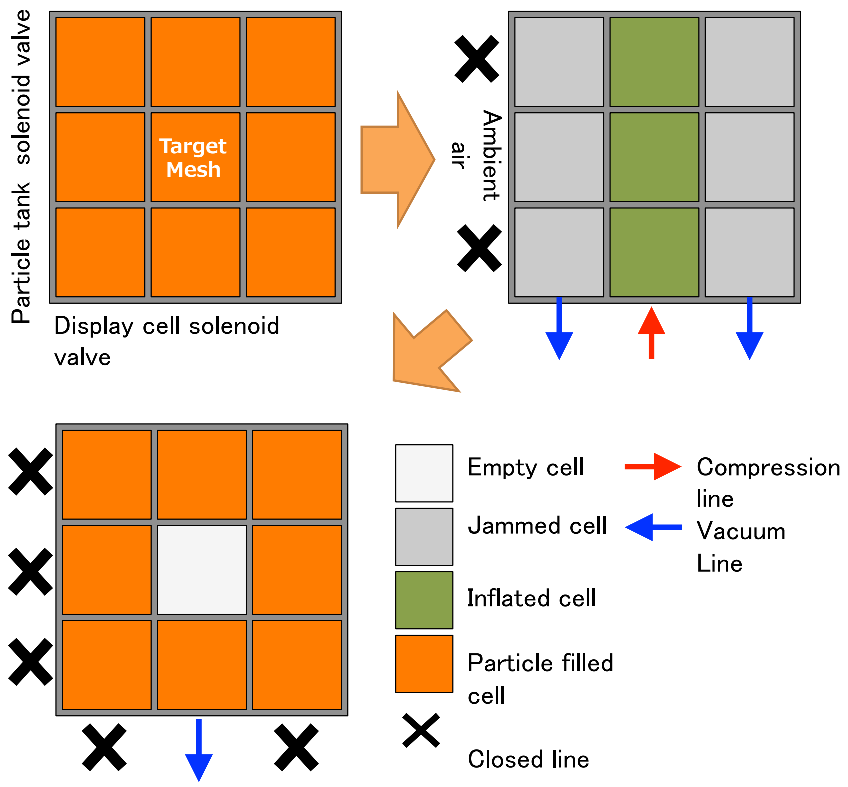

Figure 7.14: Cell shrinking procedure

mesh actuating process, by creating an air flow through a specific cells, this cells can be softened while keeping the other cells jammed and stiff.

7.2.4 Usage scenarios

Figure 7.15) show the actual actuation of this display system. .

Due to the separated mesh structure, the shape generated is discrete and particles flow between the mesh is not possible. Therefore, this type of display system is not suitable for a modeling application. Compensating the shape limitation this display has a great scalability, allow for a high resolution mesh with low-cost implementation.

We characterized this display usage scenarios as: can be utilized as a haptic display to represent a 2.5D geometry

Figure 7.15: Prototype display shape actuation state

- On screen keyboard

  Studies have found that haptic feedback significantly improves performance with keyboards on touch surfaces [8]. This display can raise a specific mesh to be used as keyboard button on flat surface. Additionally, the softness change can also be utilized as tactile feedback, resembling keyboard key pushing feel.

- Terrain model generation

  Because of this display scalability properties, in the future we plan to implemented a high resolution mesh (up to 50 x 50 mesh) display. This high resolution display can then be used to generate and visualize landscape terrain, to used for urban planning etc.

Chapter 8

Evaluation

8.1 Touch detection evaluation

8.1.1 Touch position error evaluation

In this research, we carried an experiment to evaluate the finger touch detection accuracy on different shape of surface. The experiment comprises of four types of surfaces, including touch detection on soft flat, rigid flat, rigid convex hemispherical and rigid concave hemispherical surfaces. Hemispherical surfaces have 5cm height and are 15cm in diameter (Figure 8.1). We recruited 10 university student as participants (1 female, 1 left handed), which all are experienced with touch devices; Participants were asked to touch a cross mark target that appears in random order of 9 fixed locations on the display surface with their right hand at first, and left hand at the second trial. The 8 targets are oriented in a ring with radius 50mm (linear distance) around the center target (Figure 8.2) . On convex and concave surfaces the targets are located at about 45 zenith angle.

To minimize the impact of other potential factors, we took the following measures. First, participants were instructed to touch the target without hooking with their index finger, which insures the contact point is not occluded, as noted in [7] [30]. Second, to avoid misdetection due to inadvertent motion during touching, we requested that the participants hold the finger still after the touch and then record the location 200ms after the first contact. At this time, a buzzer signals the completion of the data recording as well as indicates to the user a successful

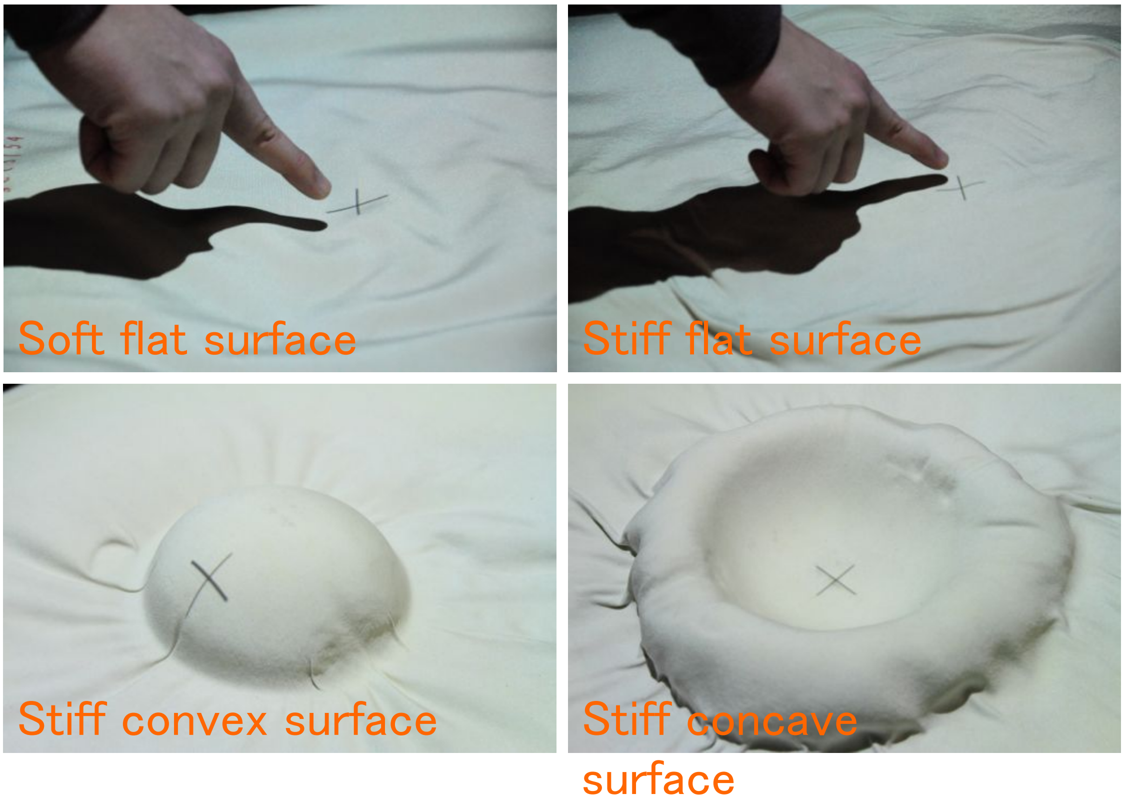

Figure 8.1: Surface state for evaluation

measurement. Finally, participants also asked to keep their head in fixed position above the surface where all the target clearly visible, controlling for parallax issues. This procedure produced 486 pointing trials(4 surfaces x 2 hands x 9 targets x 6 trials) per participant.

Figure 8.2 shows the recorded touches point during the study. The red point represents touch points by the right while blue represents those generated by the left hand. We also visualized the area that covers % of the points with confidence ellipses. Here, all contact points of all target combined showed an offset of 3.9mm (standard deviation of 1.7mm) biased to the right of target center, and there were barely any offset different between the right and left hand touch input . Figure 8.3 displays the minimum button diameter needed to cover 95% of touches point for each surface. We also grouped the target on hemispherical surface based on the slope type(uphill or downhill) and calculate the button diameter. We considered

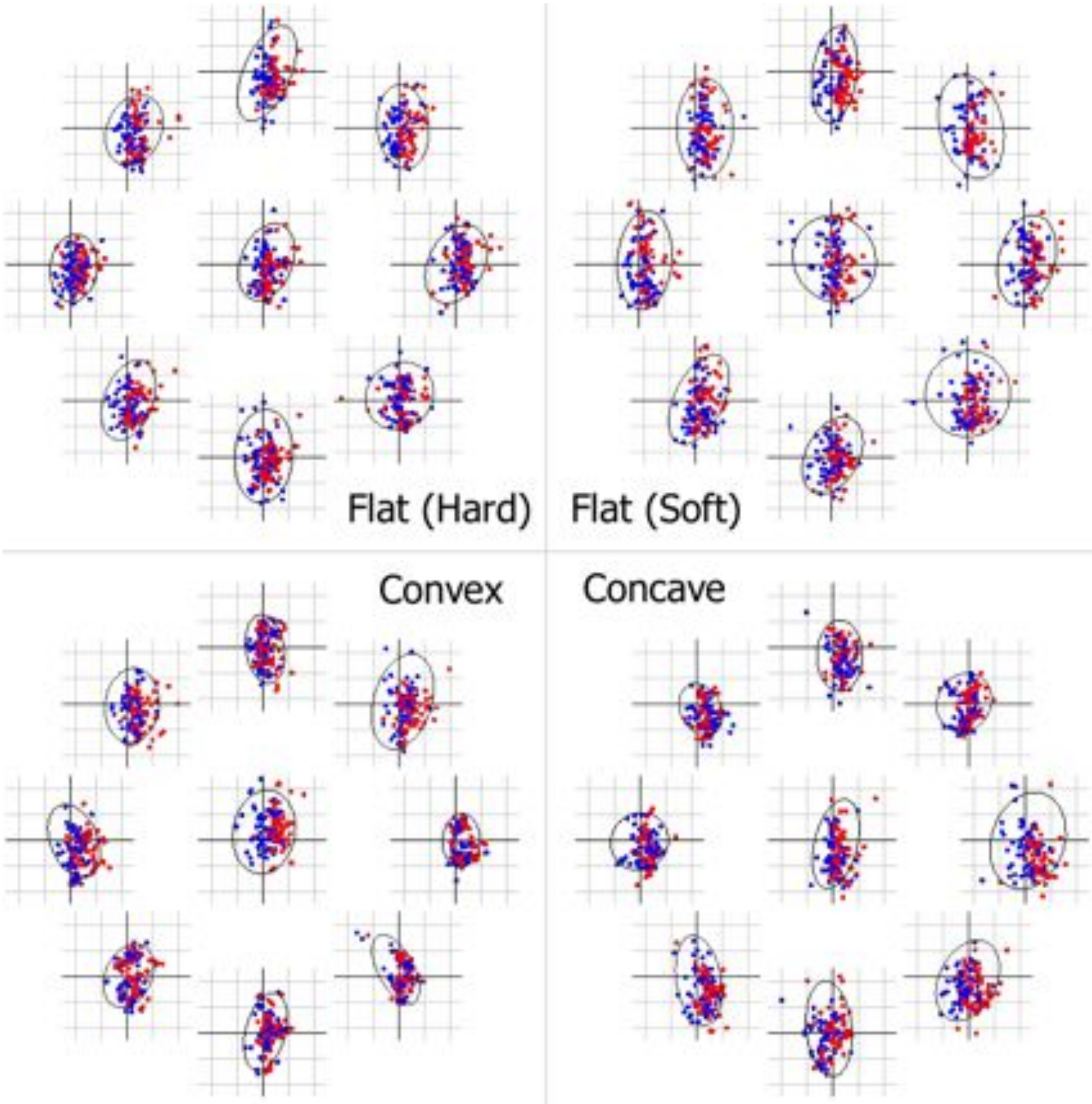

Figure 8.2: Pointing data result with 95% confidence ellipses

both of the offset and minimum button size results of rigid surfaces are in agreement with previous work on touch detection using depth camera [7](offset = 11.7mm , button diameter = 16 - 25mm) .

Based on Figure 8.3 the least accurate surface is the flat soft surface with minimum button diameter of 30.2mm. We found that the participants finger press is making the surface at tip of user finger to be sticking out. We considered this to be resulting a miscalculation of touch area due to the surface under user hand mask

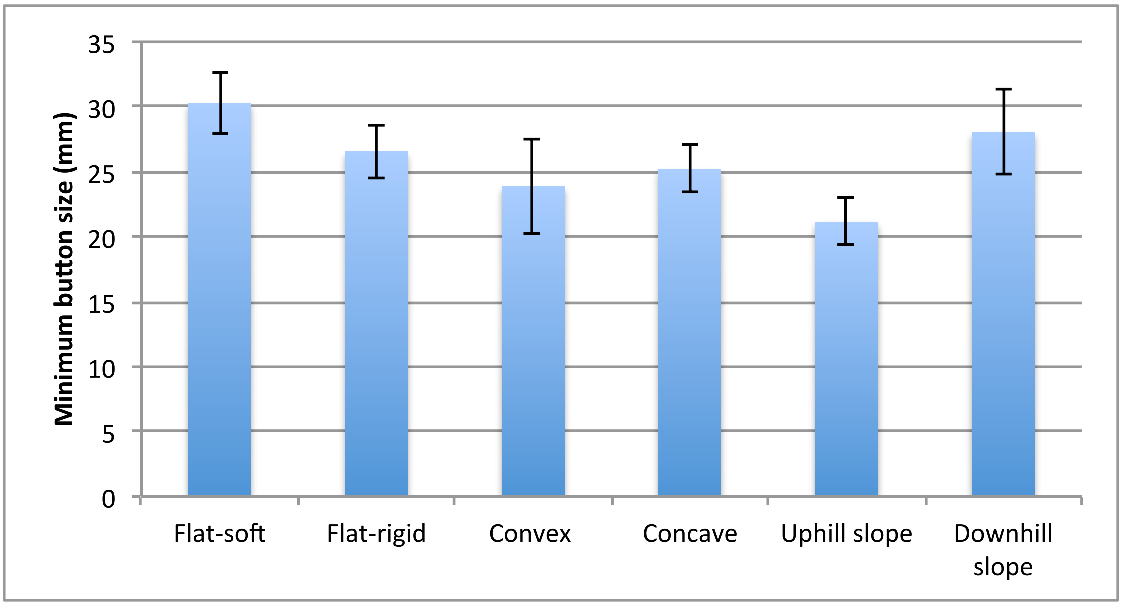

Figure 8.3: Error bars denote standard deviation across all trials

not being updated4.14 . However, with a little training a user can achieve more accurate touch detection by adjusting the touch strength accordingly with surface softness.

For the hemispherical surfaces, the convex surface has slightly more accuracy than the concave surface (23.9mm vs 25.2mm). And if we compare it based on the slopes, the uphill slope is far more accurate than the downhill slope (21.1mm vs 28.0mm). Our system determines a touch with a region within 5-15 mm from the surface. When the user finger touches a uphill slope, this region is smaller due to the angle of incidence to the finger. Conversely, when touching a downhill slope, the touching region becomes larger and the centroid is shifted from the real touch point. Both of these results are also in agreement with the previous work on touch detection on curved surfaces[30] despite a different type of touch detection (Depth camera vs FTIR).

8.2 Shape evaluation

8.2.1 Evaluation of Softness Range Variation for Modeling Modes

The most significant feature of this system is that the hardness of the display can vary continuously and freely by controlling of the pressure value. This allows the user to set the optimal hardness value according to the purpose of his/her work.

However, we do not have a direct way to perceive the hardness of unknown objects without having to directly interact with them. In addition, a general user without special training cannot imagine the hardness from the numerical values or its appearance, and so hardness control is a very blind and time consuming action.

Therefore, it is needed to design user interface that can provide the user with a more intuitive control method. In this research, we focused on those three operations: "Rough shape modeling", "Detailed shape modeling" and "Tall shape modeling", and performed an experiment to find out the hardness(pressure) range that is suited for each activity.

In this experiment, the participants have a task to copy three different types of sample models that is made by actual clay to our particle display. The sample shapes include "Simple Triangle Shape", "Face Shape" and "Bowl Shape with an overhang" as shown in the figure8.4. Then, we examined the range of the hardness(pressure) that the user uses while copying the shape to our display.

We employed eight participants(in our laboratory except the authors, 19-24 years old, six males and two females) and provide them with simple pressure up and down buttons usable for copying shapes. These two buttons can gradually increment or decrement the pressure value, one push is 1/1024 of the width range of the pressure sensor (about 0.25kPa) In addition, we requested the participants to copy the sample shape in the order of triangle, face and bowl after explaining how to use the buttons and providing 1 minute of practice.

Then, we also requested each copying task to be done "fast and as accurately

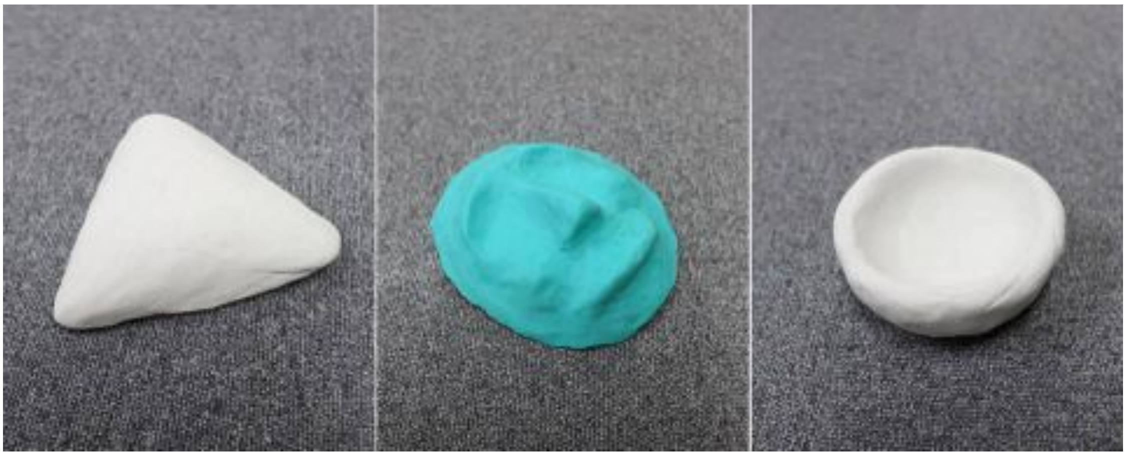

Figure 8.4: Sample models

Figure 8.5: Created models by participants

as possible" and "increase and decrease the hardness as necessary for your task". The result of this experiment is shown in the figure8.6.

This graph shows the average pressure value that is used by each participant to copy three different shapes with standard deviation. According to these graphs, we found the low softness value(-1kPa) has been used for modeling a simplest triangle shape, in contrast, higher softness value(-2.6kPa) is used for modeling of other two complex shapes. Based on this result, we also adding a color range into the modeling stiffnes control slider, indicating the user the suitable softness range for each modeling procedure (blue for rough shape, and red for detailed shape

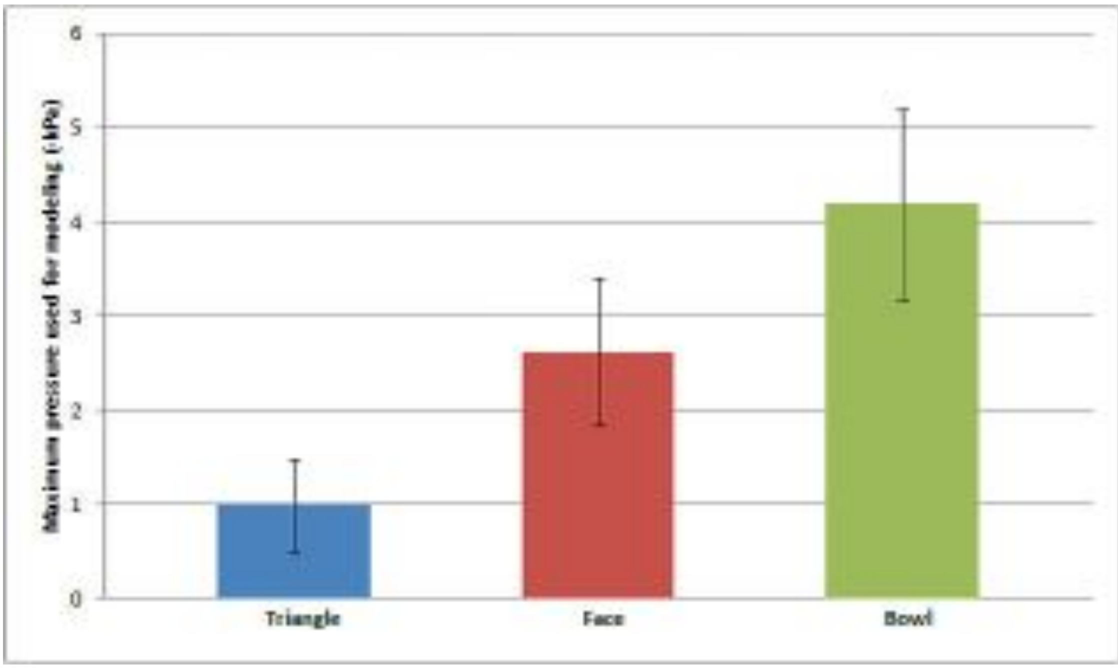

Figure 8.6: Average pressure value with standard deviation

modeling)(Figure 8.7).

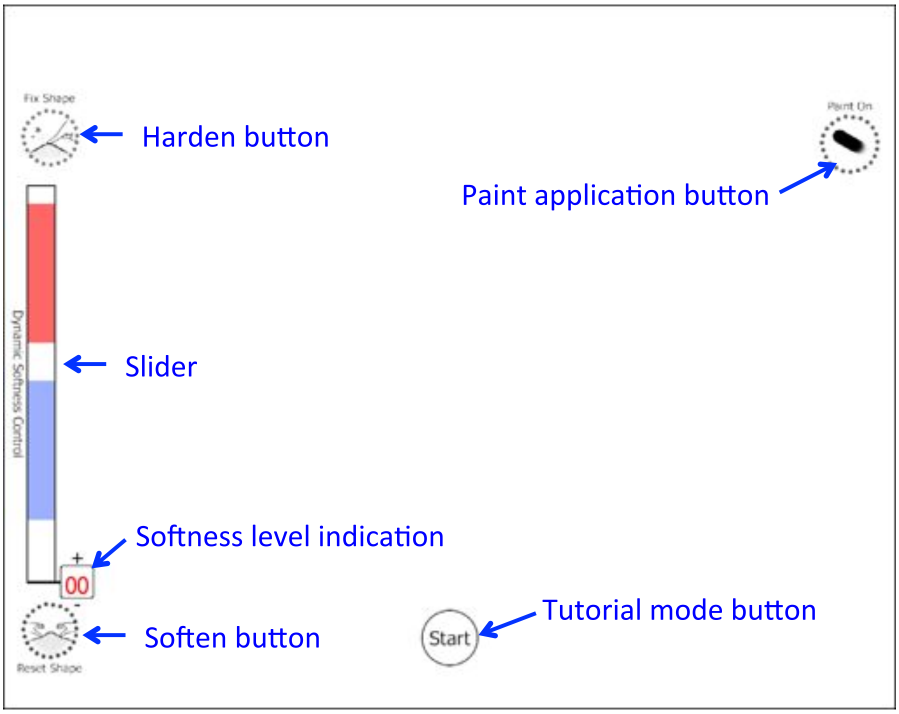

Figure 8.7: Projected color range on the slider

Chapter 9

Discussion

9.1 Limitation

9.1.1 Shape Limitation

The shape modeling capability of our system is subject to some limitations stemming from limited particle amounts and area/flexibility of the display surface fabric. For example, if the user made large convex shape at one part of the display, the user need to gather large amount of surrounding particles. This prevent the user(or another user) from creating new shape at another part of the display.

In current prototype, the maximum height of the shape is about 15cm. When creating a high convex shape in the display, it is necessary to pull the surface fabric with substantial force. Since a stronger force is required for tall shapes, the system cannot decrease the stiffness state of the surface to sustain the height of the shape. In order to address these limitations, more flexible cloth will be needed. This however may lead to decreased surface elasticity due to permanent fabric stretching and increased durability loss. To address this problem, we are developing new mechanisms for dynamic change of both surface volume and surface fabric area.

Display stiffness also depends on the thickness of the particle layer. If the user makes a shape that is quite detailed having parts of less than 3cm in width, the shape may be easily deformed mistakenly by hand or gravity even if the system is in the hardest state.

In order to make modeling operation easier and more efficient, vacuum molding tool can provide some primitive shapes(circle, rectangle, triangle, etc...) that can be used as design foundation. In particular, in the case that the target shape is clearly specified, the system can have pre-shaped molding to support ease of shaping. This enables the user to design the shape changing only the details of the preset shape. Furthermore, visual geometry information such as dimension or current height can be directly projected on the shape and could be used for modeling navigation.

9.1.2 Touch Detection

In the process of updating the background, we used a rectangular area larger than that of the actual hand as a mask image to avoid the noise at the boundary of the hand region in the depth image. This became a problem when a user performs modeling work without moving his/her hands as the region below the users hands may have not yet been updated. In order to reduce the occurrence frequency of this problem, reducing the size of the hand mask area by introducing noise reduction processing to current algorithm is suggested.

We move on to discuss the limitations or potentials of the overhead depth camera. First, it is impossible to use an overhead camera to capture the contact surface (base) of the finger. In this implementation, we detect finger touch by detecting the top side of the finger surface that is less than 15mm away from the surface. This may result in false-positive/false-negative detections if the userfs fingertip is thinner/thicker than the height threshold. In order to address this problem, we consider the method of using multiple low height depth cameras fixed on the boundary of the display to increase visibility of contact side of the fingertip. Multiple cameras may also be needed to capture the whole area of the convex/concave shapes that have overhanged parts or steep angle surfaces relative to the camera angle.

The offset between the position detected and that of the intended position of user touch was found to be a result of many variables: individual differences in the thickness of the finger, the parallax occurring from viewing angle, or other reasons (calibration errors, etc...). To address this problem, visual feedback can be used by displaying current fingertip position on the surface using visual effects when the users finger approaches the surface.

9.1.3 Responsivenese

The responsiveness of pressure control speed depends on the air volume(size of the display) and the displacement of the vacuum pump. In this current prototype system, which utilizes a single linear piston pump(with 40L/min displacement capability), it takes about three seconds to fully harden the soft surface. Although current linear-piston pumps have enough decompression capability to harden the surface, the decompression speed was not found to be of acceptable levels due to the low displacement capabilities of the pumps. Therefore, we plan to employ different types of pumps, such as an air blowers that have high displacement capability in combination with the current vacuum pump to allow for fast air displacement.

In addition, a vacuum tank and an air compressor can be used together decrease response time of changing stiffness. High response pressure control can generate even more tactile sensations when the user pushes a button on the surface making haptic vibrations from sudden pressure changes possible.

9.1.4 Material and Durability

First, we discuss the characteristics of particle materials choice. Particle size is a very significant factor to determine tactile characteristics. A small/light particle is well suited for the display material filler. The size of the particle and thickness of the surface fabric affect the resolution of the shape that the user can create on the surface. Smaller particles and a thin surface material would allow the user to create a finer, more detailed shape on the surface.

Also, if an external force is applied to the display, the smaller/lighter particles would react in a smoother fashion, giving a more aesthetic look and feel to surface manipulation. It also leads to reducing manipulation load on the users finger for long term operations. In addition, light weight particle prevents the surface from collapsing its own weight due to gravity.

If the display pressure is reduced, the shape of the individual particles will appear on display surface due to the space between the particles and surface fabric coming into very close contact. If the particle size is larger, it will result in visually unpleasant textures (similar to goose bumps) as well as increases the friction experienced when dragging the finger across the display surface.

The size of the particle also affects the air volume inside the display volume. Using smaller particles reduces the overall volume shrinkage of the display under decompression and increases the response time of internal pressure change. On the other hand, non-spherical particles can be used to create various levels of friction against finger movements and even provide the user with different and unique tactile sensations. Therefore we plan to continue this study in regards to particle material.

We demonstrated this prototype system at an international conference for five days (about five hours total use per day) and no substantial damage were found on the particles and display surface. There were slight darkening and fabric stretching, as well as an increase the amount of air leakage all considered to be due to the deterioration in lining and general wear and tear. The maintenance in this case is not difficult due the material being inexpensive and easily replaced.

9.1.5 Modeling works

How good are people in using this device to generate geometry. To be able to create or copy a fairly complex geometry i.e. human face, user need to first understand a few limitations of our surface.

First, after creating the model base and make the surface harder (to maintain the shape) ,it is rather difficult to move more volume into the model base. Therefore, the user needs to estimate the required total volume while building the base (most of the user we observed were making the base as big as they can so they don't need to think about the volume margin).

Second, to modify a detailed shape, user needs to lower the hardness first and then start over the detailed part. However, some people were able to modify the detailed shape using brute force without lowering the hardness. This method will resulting with wrinkles appear on the surface, making the look not so neat. By considering all these measures, some people did a really great job on creating or copying a complex shapes.

9.2 User Feedback

In this research, we conducted a preliminary user study to observe how a first time user performed with our device. We employ 7 participants to operate our modeling application, and asked them the feedback. Initially, some of the participants commented that it was hard to control the appropriate hardness at the first time, because the relation between the hardness and the slider was not clearly apparent. However, after a few attempts of manipulating the slider and obtaining a feel for the hardness using physical touch, the user was able to use the modeling application from model shaping (early stage) to texturing (finishing touches). Participants also commented that dividing the slider with color area based on the suitable hardness for different type work i.e.: blue for rough shape and red for detailed shape modeling was helpful for choosing the surface malleability. Finally, most of the participants stated right away that the tactile feeling when the hardness changes dynamically was quite appealing, making the surface feeling like an organic material than an artificial material.

Figure 9.1: Sample of model created by user

9.3 System Comparison

In this research, we introduced a deformable display with stiffness control called "ClaytricSurface" system, and proposals of a particles display shape actuation called "LivingClay" system.

We summarised and compared both the systems cappabilities and limitation as shown in table 9.1.

9.4 Future application and Possibilities

In the future, we plan to extend current single particle layer to multi-layered and individually controlled structures. For instance, in two-layered particle display, if the upper layer is softened and the lower layer is hardened, the user can change the general shape of the model whilst leaving the fine details on the surface. Multi-layered particle volumes also have a possibility of generating complex tactile

Properties	ClayticSurface	LivingClay	
		Array actuator	Multiplexed mesh
Variable stiffness	○	○	○
Traditional flat-rigid surface	○	○	○
Over-hanged shape	○	○	×
Shape actuation	×	○	○
Scalability	–	low	high
Mobility (size reduction)	possible	very difficult	slightly difficult
Modeling application	suitable	suitable	not suitable
Substantial shape hand deformation	○	○	×
Detailed shape hand deformation	○	○	○
Localized stiffness change	×	×	○

Table 9.1: System comparison

sensations.

For future applications, we also plan to develop interactive visual/tactile displays that can support training or rehabilitation of finger muscles. We also want to look into the possibility of controlling the applied load to the fingers during operation to prevent finger stress by dynamically changing the local stiffness of the display according to touch pressure.

Chapter 10

Conclusion

10.1 Summary

At first chapter, we introduced the nature of the research, including the problem that are observed/assumed to exist. It also has look at the objective of the research in regards to the defined problem

In second chapter, we discussed related research and previous work on Organic User Interface with capabilities of mechanical properties change and shape deformation.

In third chapter, we introduced vacuum jamming as an effective method to control display stiffness. We also described the particles selection consideration and evaluate the pressure-softness relationship.

In fourth chapter, we described the implementation of our proposed display, including the stiffness control, touch input detection, and gesture detection.

In fifth chapter, described the implementation of modeling application for interactive surface with controllable stiffness.

In sixth chapter, we explored the usability of particles pneumatic conveying technique as a new display actuation method allows for both volume change and stiffness control.

In seventh chapter, we introduced design of interactive surface with controllable softness and shape deformation including application and usage scenarios.

In eighth chapter, we evaluated our implemented system, including the touch detection and appropriate stiffness for modeling works.

In ninth chapter, we discussed our proposed systems limitation and capabilities.

In tenth chapther, we concluded the research and comments on this research contributions.

The contribution of this research can be summarized as follows:

1. Evaluation of pressure vs stiffness relation for shape deforming purpose.
2. Implementation of variable stiffness display with a high range and detailed softness variation.
3. Implementation of depth camera based touch detection, that allow dynamic surface deformation.
4. Development of modeling application with capability to change surface stiffness coressponding the modeling work.
5. Proposal of new display shape actuation that allows volume change using pneumatic conveying method including stiffness control.
6. Design of array actuator system allows for complex shape deformation and low-cost scalable control system.

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Appendix A

Published Paper

[1] Jefferson Pardomuan, Toshiki Sato, Yasushi Matoba, Hideki Koike. ClaytricSurface: Interactive Deformable Surface Display with Dynamically Controllable Softness. In Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces, ITS '12.

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