Design of High-Resolution, Low-Cost Tactile Shape Display

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CONTENTS

The aim of this project was to create a $2.5D$ shape display and to explore the usage of magnetic actuation techniques while examining the plausible use of unique materials. To do the same, a comprehensive study was made of currently available actuation methods. The project was completed using open source materials to reduce construction and implementation costs while maintaining a high level of performance. This can provide future researchers a cost-effective platform to delve into large-scale applications of the shape display created. At the final stage of the project, an open-ended online survey was conducted to crowd-source various possible uses for the shape display that range from medical to military and commercial scenarios. The iterative method used to develop the display helped to refine the components of said display with each consecutive iteration by thoroughly testing and evaluating during each phase. Though there are limitations due to currently available technology, we remain hopeful that they can be overcome. The scope for technological improvements regarding both input and output methods as well as for the process of actuation itself is high. This paper suggests standardisation, collaboration and regular evaluation among members of the scientific community to help move $2.5D$ shape displays into the future.

1 INTRODUCTION

In the modern world, data is being created at an enormous pace[1]. Most of these data are locked up as virtual entities in large data centres across the world. Access is mostly restricted to view these data in a $2D$ representation, provided by screens that can range in size from few centimetres wide of a smart watch or large screen televisions.

Many researchers are working on two distinct approaches in enabling users to access this vast amount of data. One of the approaches is to make the human virtual using technologies like Oculus Rift (Firth, 2013). An alternative method is to make the virtual data real via technologies like inFORM by Follmer, Leithinger, Olwal, Hogge, and Ishii (2013) and Ishii, Leithinger, Follmer, et al. (2015).

This leads to concepts of a tangible display, a type of display that, as the name suggests, is tangible. These types of displays can be physically manipulated and enable natural expression of intention by the users. In this paper, we reflect on Shape Display (also called as $2.5D$ displays), a form of tangible display. Shape displays can be considered as an embodiment of tangible displays, wherein shapes are rendered based on digital inputs received by the device.

Shape displays have a long history of over two decades, in which researchers have explored its various potentials. The decisive challenge is to manufacture shape displays. Numerous implementations of shape displays are available in the academic world, which have been used by researchers to carry out specific research tasks.

The shape display designed as part of this project consists of a $20x20$ element matrix that can be actuated with a single $3D$ moving controller scanning lines and rows. In a matter of minutes, it can create a $3D$ depth representation of any given source depth map image. Additional goals of this project are to perform methodological progress to the underlying mechanism and technology for actuation. It was also important to ensure that this project delivered a shape display that was compact, easy to handle, and be easily moved around. At the same time ensuring the cost of the design to remain low. A low-cost design of shape display enables a larger audience to engage with the technology and help improve it by utilising contributions from a wider hacker/tinkerer community. *Figure 1* shows a shape being rendered on a shape display. *Appendix 9.4* contains more examples of shapes rendered by the shape display designed and manufactured by this project.

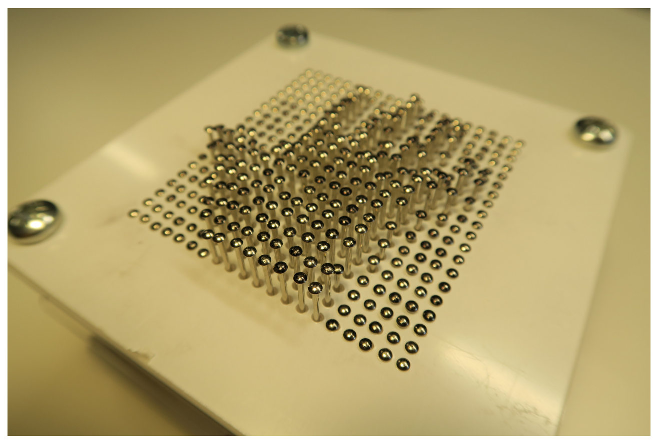

Figure 1. Rendering of a palm on the shape display

2 LITERATURE REVIEW

In this section, we discuss relevant related work for the design of a tactile shape display, synthesizing, actuation, input and output mechanisms.

Traditional Graphical User Interfaces (GUI) interfaces utilise senses like sight that are supplemented by sound as an additional factor for feedback. The largest sensory organ that can sense touch, pressure, temperature with a total area of about 20 square feet[2], remains underutilized in many multimodal interaction systems. Newer touch screen interfaces that became popular among consumers with the advent of the

[1] http://aci.info/2014/07/12/the-data-explosion-in-2014-minute-by-minute-infographic/

[2] http://www.mcwdn.org/body/senseorgans.html

iPhone (Grossman, 2007) creates a new arena where touch-based interaction is the norm.

More recently research and industry began to extend the tactile output capabilities of multi touch screens through added haptic feedback. For example, recent research prototypes including H. Iwata (1998), Iwata, Yano, Nakaizumi, and Kawamura (2001) and Rovan and Hayward (2000) utilise haptic feedback mechanisms. Some commercial products also have added vibro-tactile feedback to screens or interfaces such as the Force-touch-pad[3] or Taptic Watch Engine[4].

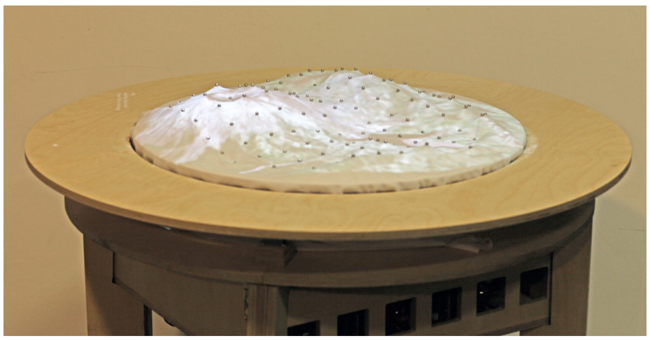

Figure 2. Example implementation of shape display; Relief by Leithinger and Ishii (2010)

In the case of the evolution of touch interfaces, it is important to progress along the level of richness of interaction that can be enabled in touch-based interfaces. Jahng, Jain, and Ramamurthy (2007) assumes higher the level of richness of interaction the more immersive the experience. The richness can be improved by adding multiple factors that can be sensed. For example touch, pressure, temperature, vibration, pain and itching. Though the latter two may not be useful for a positive experience. Richer experiences can be helpful in creating simulations or for *serious games* (Michael & Chen, 2005).

Triangles a project by Gorbet, Orth, and Ishii (1998), creates a manipulatable triangle based configuration, which are physically interconnected. The connection creates electric pathways that represent a particular geometric configuration. This system allows for two handed tactile interaction, representing simple as well as complex information of physical space translated into a digital experience. Though the triangles can be appropriated for various interactions, the key interactions in this paper is non-linear storytelling.

Tang and Beebe (2006) explores the potential of using tactile feedback in creating assistive navigation technology for the visually impaired. The key differentiator in this implementation is the location of the tactile interface. In the paper, palate has been explored in creating a tactile interface showcasing an interesting concept as a navigational aid.

Projects such as Block Jam by Newton-Dunn, Nakano, and Gibson (2003) or Lumino by Baudisch, Becker, and Rudeck (2010) use computational blocks that contain a certain number of pre-defined interactions, usually a click input and a screen output with potentially a vibro-tactile feedback.

Illuminating Clay, a project by Piper, Ratti, and Ishii (2002) is an interesting example that uses a projection mechanism along with topographic sensors to reinforce topographical data onto the projection surface. This approach is created for a specific purpose of landscape analysis.

In this section, we explore various prototypes of shape displays that have been discussed in the literature, experiments and technology previews. Many of these displays might contain proprietary technology that has not been publicly disclosed. Even for systems where technical details were not fully disclosed, technical specifications were derived from the information given, illustrations, and additional information as described in the following classification of shape display technologies.

2.1 Classification of Shape Display Technology

Due to the engineering complexity of building $3D$ actuators for shape display, most prototypes explored and described in the literature have a relatively low resolution and display density. They range from $3x3$ to larger displays containing up to 7000 actuated display points. It is to be noted that the 7000 point shape display is an advanced display, high cost, and used mostly for government/military projects. Most shape displays have a size between $3x3$ and $13x13$.

These displays can be classified based on their resolution, display density, actuation depth and the technology used for actuation.

2.1.1 Terminologies for Shape Displays

Resolution : Like any traditional screen, resolution is the number of display elements that are placed in each of the axes. These values are represented in a x b format.

Display Density : Display density describes how spread apart the display elements are placed within the system, it defines how tightly the display is designed. The typical method of representing this information is the unit PPI, which stands for pixels per inch. See *footnote 6* for why PPI is used for this measure. It is important to note that display density is calculated based on the diagonal length of any display.

Actuation Technology : The physical technology that is

[3] https://support.apple.com/en-gb/HT204352
[4] http://www.telegraph.co.uk/technology/apple/11466498/What-is-Apples-Taptic-Engine-and-Force-Touch.html

	Year	Actuation Technology	Resolution	Depth (mm)	Size (mm^2)
Kontarinis, Son, Peine, and Howe (1995)	1995	SMA wire	6 *x* 4	3	12.6 *x* 8.4[a]
Surface Display by Hirota and Hirose (1995)	1995	Slider-crank Mechanism	4 *x* 4	50	120 *x* 120
Fukuda, Morita, Arai, Ishihara, and Matsuura (1997)	1997	EM Actuator	3 *x* 3	2	13.5 *x* 13.5[a]
FEELEX by H. Iwata (1998)	1998	Motor driven screws	6 *x* 6	80	240 *x* 240
Caldwell, Tsagarakis, and Giesler (1999)	1999	Pneumatic	4 *x* 4	10	15 *x* 15
Hayward and Cruz-Hernandez (2000)	2000	Piezo Ceramic	64 (8 *x* 8)[b]	20	12 *x* 12
FEELEX 2 by Iwata et al. (2001)	2001	Piston-crank mechanism	23	18	50 *x* 50
Wagner, Lederman, and Howe (2002)	2002	Servo Motors	6 *x* 6	2	18 *x* 18[a]
Pasquero and Hayward (2003)	2003	Piezoelectric Bimorphs	10 *x* 10	5.5	10 *x* 10
Nakatani, Kajimoto, Sekiguchi, Kawakami, and Tachi (2003)	2003	SMA (Bio Metal Helix)	4 *x* 4	120	80 *x* 80[a]
Digital Clay by Rossignac et al. (2003)	2003	Hydraulics	5 *x* 5	48	25 *x* 25
I. Poupyrev, Nashida, Maruyama, Rekimoto, and Yamaji (2004)	2004	Shape Memory Alloy	5 *x* 5[b]	Low[b]	—
Howe (2004)	2004	SMA & Servo Motors	6 *x* 6	4	10 *x* 10[a]
Xeno-Vision Mark III by Page (2005) Magazine (2015)	2005	Electric	7000	150	910 *x* 1220
Lumen by Poupyrev, Nashida, and Okabe (2007)	2007	Nitinol Actuators	13 *x* 13	6	84 *x* 84
Anti-gravity Z actuator by Hazelton (2008)	2008	Magnetic	—	—	—
Relief by Leithinger and Ishii (2010)	2010	Belt Actuation	12 *x* 12	130	450 *x* 450
Leithinger et al. (2013)	2013	Motor	12 *x* 12	100	425 *x* 425

[a] These values have been inferred from the details presented from the paper.
[b] Data inferred from pictures within the paper.

Table 1. List of major Shape-Displays that have been discussed in the literature. Part of this list has been sourced from Leithinger, Lakatos, Devincenzi, Blackshaw, and Ishii (2011)

used to drive the display. The technology is used to induce displacement for display elements.

Depth : Depth or Height can be used interchangeably, this is a measure of how much a display element can be moved from its baseline. Larger the value of depth, larger the relief that can be showcased with that display system.

Various actuation methods have been explored in literature, each with its unique set of advantages and disadvantages. In *table 1* we explore different displays based on their technology used for actuation, and the resolution along with other important parameters of the display. These displays use servo motors, shape memory actuators, piezoelectric and piezo ceramic technologies. Other technologies explored were electromagnetic actuators and pneumatic actuators. The following sections explores few of the top actuation technologies and how they work.

2.1.2 Servo Motors and Stepper Motors

A servomotor can be either a rotary actuator or a linear actuator that can be used for precise positioning. The positioning could be either angular or linear depending upon the type of servo motor used. A general construction of servo motors has a suitable motor linked with sensors to detect and give feedback on position.

A stepper motor is similar in nature to a servo motor, but it consumes power and is running to lock the position that it has been instructed. Although they are quite comparable, their performance characteristics differ.

In any stepper motor or servo motor design, it is important to understand the available torque of the motor system as this defines the amount of weight it can carry and how fast it can accelerate to the desired position. This is valuable if the motor system is working against gravity to lift either itself or other objects. Suh, Kang, Chung, and Stroud (2008) explores further details of servo motors.

2.1.3 SMA or Shape Memory Alloy

Shape Memory Alloys (SMA) have many other alternative names including, smart metal, smart alloy, memory metal or muscle wire (Fremond, 1996). The key concept of an SMA is that it “remembers” its original shape and its deformed shape. SMA are typically made from alloys of copper, aluminium and nickel; alternative forms use nickel and titanium. Costlier versions use copper, gold and iron. SMA actuators are enabled when electricity is passed through it, causing it to heat. This heat causes deformation to occur within the material hence inducing physical motion. Precise control of SMA can be achieved by passing different amounts of electricity and calibrating it.

2.1.4 Piezoelectric and Piezo Ceramic Actuators

These types of actuators use piezoelectric materials. Certain materials like quartz, exhibit piezoelectric properties, if pressure is applied to the material it produced corresponding electric impulses. The reverse principle is the key concept behind piezoelectric actuation, in which you pass electricity to cause actuation with the materials.

Traditional piezoelectric mechanisms induce a minor displacement for a large amount of material. Some techniques use inbuilt mechanisms to amplify the actuated output. Choi and Han (2010) drills down into further details of this actuation technology.

2.1.5 Exploring Shape Displays

Depth of travel of 2.5D Shape-Displays, ranges from 1 *mm* to 150 *mm*. Whereas the display size ranges from 1x1 *mm* to 450x450 *mm*.

The common approach among these methods is the use of single actuator for a single display unit or an actuated pixel. The term pixel or picture cell does not fully encapsulate the concept of an actuated shape display. Thus in this document we refer to these individually actuated cells as display elements. Different papers refers to these elements differently, such as *Emancipated Pixels* by Iwata et al. (2001), *Shape Pixels* by Hardy, Weichel, Taher, Vidler, and Alexander (2015), *Tactile Pixels* by Bhattacharjee, Rehg, and Kemp (2012). In some cases, the elements are named based on the actuation technology used, for example, *Natto Cell* described by Yao et al. (2015) which derives its name from *Bacillus natto* the former name of *Bacillus subtilis*.

Shape displays designed with individual actuators per display element pushes up the cost at the same time making it modular. If actuation mechanism of individual display element breaks down, it can then be easily replaced by changing the single actuator of that element.

There are notable exceptions to the traditional actuator based approach for 2.5D shape display. Projects like Illuminating Clay by Piper et al. (2002) and Sandscape by Ishii et al. (2004) bring in a concept of continuous tangible user interface, by using materials like Clay or Sand offering a very high resolution of interactive yet tangible object for engaging with the users.

There has been other novel exploration of ideas like a fictional liquid-shift material by Leigh (2015) which can change its phase, shape, and weight distribution. A realistic implementation of the weight and volume changing object has been explored by Niiyama, Yao, and Ishii (2014). The realistic implementation uses liquids of various densities pumped into a bladder to alter its shape and its overall weight, this can be used in different artefacts of tangible elements to simulate objects that can change in weight. A fictional example could be a weight changing phone that can inform its battery status based on a shift in weight or volume of the device.

Most systems that encompass shape displays are within the realm of physical, chemical and electronic engineering. Some have explored bio-engineered shape displays that present unique challenges and opportunities for researchers in shape displays. A few of the notable examples include bioLogic by Yao et al. (2015) and Bio Print a project by Ou, Yao, Della Silva, Wang, and Ishii (2014). Both of these projects, use *Bacillus Subtilis*[5] spores as actuators. They are actuated by changing the relative humidity exposed to the bio sheets.

2.2 Interfaces for Output or Feedback

The interfaces of the 2.5D displays discussed in the literature range from single to multi-modal output mechanisms. Typically the basic experience requires a touchable, active shape output interface that can be supported by visual representation either by projection or by lights from other sources. Audio output is another potential method for expressing the output or to work in conjunction with the shape output of a 2.5D display.

One of the key contributors to the quality of output for the shape display is the limited resolution of the displays that are currently being developed. Through modern methods and new technologies, the resolution of the displays is likely to improve. Current techniques involve creating an approximation of the actual model.

Other limitations include the inability of 2.5D displays to render overhangs. There are approaches to augment with projected displays to address overhanging issues as well as to create a *faux* perception of higher resolution via projected images. *Figure 3* illustrates the impacts of overhangs and clipping.

Research work including, Illuminating Clay by Piper et

[5] *Wikipedia:* Bacillus subtilis, known also as the hay bacillus or grass bacillus, is a Gram-positive, catalase-positive bacterium, found in soil and the gastrointestinal tract of ruminants and humans.

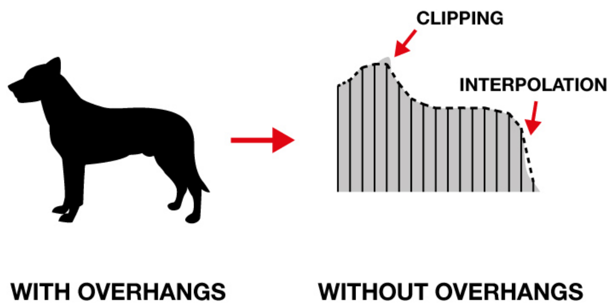

Figure 3. Overhang as described in Leithinger et al. (2011)

al. (2002), Sandscape by Ishii et al. (2004), Sublimate by Leithinger et al. (2013) utilises overhead projection techniques, whereas Shadow-free Interaction by Shimba and Lee (2014) presents a technique for rear projections that eliminates shadows cast by overhead projection mechanisms. FEELEX-2 by Iwata et al. (2001) was one of the earliest implementation of a $2.5D$ shape display to have a projected image on top of it to accentuate the displacement portrayed by the device.

Individual display cell of the shape display could potentially be used to provide additional information or related output. For example Pneuxel by Yao (2014), Lumen by Poupyrev et al. (2007) outputs a single pixel resolution display at the end of each actuating element of the shape display. This system can potentially be expanded to use Liquid-crystal display (LCD) screens to convey texture information.

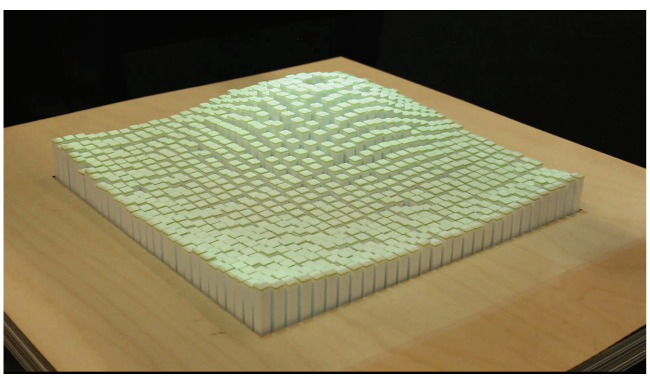

Figure 4. Follmer et al. (2013) implements a tangible shape display to implement the conceptual Marble Answering Machine designed by Crampton Smith (1995)

2.3 Input Mechanisms

Shape displays provide a potential method for receiving input for computation. These input mechanisms can be classified into the categories based on the type of sensors used. *Table 2* lists top sensor mechanisms that are used in various shape displays. Though this showcases only a few direct sensor types, there could be other sensors including motion tracking, body tracking and sound based sensors.

Apart from the traditional set of sensors like buttons for inputs there have been a few methods such as using modelling materials or clay to mould shapes (*manipulation*) for input as discussed in papers including Illuminating Clay by Piper et al. (2002) and Sandscape by Ishii et al. (2004).

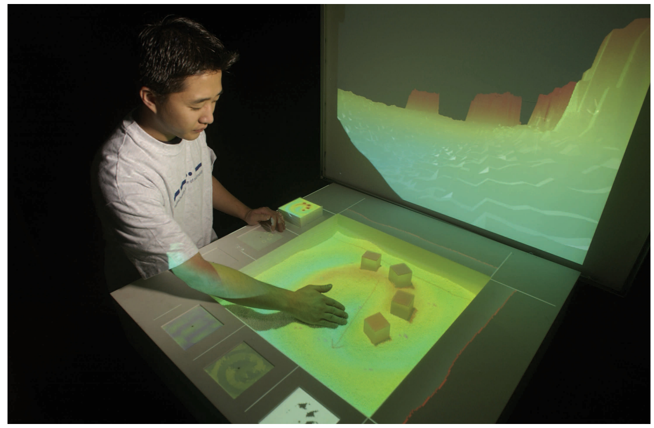

Figure 5. Sandscape as described in Ishii et al. (2004)

Project BlockJam developed by Newton-Dunn et al. (2003) creates a whole interface that can be considered as an input and output tool. It utilises simple button (*pressure*) for click type input and an array of optical infrared reflectors (*occlusion*) in a predefined path to sense a dial gesture.

An array of linear electric slide potentiometer (*motion*) is used in addition to the traditional touch based buttons in project Relief by Leithinger and Ishii (2010) (see *figure 2*) and by Leithinger et al. (2011) to capture user input through a malleable surface.

Kontarinis et al. (1995) uses an array of capacitive tactile sensors (*pressure*) to sense a change in capacitance by varying the distance between copper strips spaced with thin strips of silicone rubber. This method helps in identifying pressure applied to the surface.

Temperature sensors can be potentially used to collect additional input from the users. The time taken to sense changes in value could be fairly high for small changes from the ambient room temperature. This could be a potential deterrent from it being used. Temperature sensors are effective in a closed environment like tactile gloves; for example Teletact and Teletact II as discussed in the book by Brewster and Murray-Smith (2003).

Shape displays offer interface developers, a new method to create interaction models with an assortment of input mechanisms. Apart from the listed sensors there could be other

Sensor Type	Potential Use
Pressure	Quantify input at a particular location
Touch	Identify location of the interaction
Motion/Movement	Physical motion, quantity of actuation along with feedback based on pre-configured resistance
Occlusion / Light	Identify location of the interaction
Temperature	Similar to pressure sensor but utilise temperature as another factor for the weight of input at a particular location in space.
Manipulation	Ability to sense deformation / formation of shapes of various materials

Table 2. Partial list of sensor types and how they could be used for input of various kinds.

sensory mechanisms that can act independently or in conjunction with other input tools. For example PneUI, a project by Yao, DeVincenzi, Pereira, and Ishii (2013) uses direct touch along with near range proximity measurement. This is achieved by measuring the capacitance between human fingers and the electrodes in the system.

2.4 Use of Tactile Shape Displays in HCI

St John, Cowen, Smallman, and Oonk (2001) has studied the use of $2D$ vs. $3D$ displays for tasks involving understanding of shapes. The paper argues three-dimensional views are useful for shape and layout understanding as they integrate all three dimensions in a single rendering and is receptive to additional depth cues. Though the paper talks about the advantage that the $3D$ displays can showcase features of an object which may potentially the biggest pitfall of a $2.5D$ shape display. This can be enhanced by the use of overhead projectors to the shape display to relay additional information as explored in projects like inFORM by Follmer et al. (2013).

Leithinger et al. (2011) in his paper argues that $2.5D$ displays in addition to the joint representation models can be extended to wider use cases by increasing the vocabulary of interaction methods. The document defines a set of gestures for selection, translation, rotation of shapes in the display, along with copy-paste gestures to quickly duplicate shapes.

The history of shape displays in scientific literature exhibits its advancement over the last few decades. It has evolved in its ability for interaction using modern sensors and engaging output mechanisms while forging ahead with the actuation technologies. The field of shape displays are accelerating at an incredible pace, particularly fuelled by the modern world of Internet of Things (*IoT*) as explored by R. H. Weber and Weber (2010).

Ishii, Leithinger, Yao, Follmer, and Ou (2015) envisions a future where materials can change form and properties dynamically, becoming as reconfigurable as pixels on the screen. Along with a vision where there exists an embodiment of all digital data as physical manifestations so that users can interact directly.

2.5 Summary of Related Work

In this section, we explored the existing shape displays from various aspects. Shape displays have been explored on their actuation mechanisms, input/output strategies and how they are a part of modern interaction methods. Notable shape displays analysed in this section has helped in eliciting the design principles (*see section 3.3*) for this project thereby defining the project. The key factors for any shape display are, actuation, resolution, display density and the physical size. All implementations that can be seen across literature has certain common features. Most systems have individual actuators, which means there exists an actuator for each display element for the system, this in turn pushes up the cost of the system as well as the size of the display. In general independent actuation mechanisms utilise a push type actuation of the display element, either using servo motors, SMA wire or other technologies. To recap, our design differs and provides a low-cost, high resolution (albeit slower) actuation mechanism for $2.5D$ shape displays.

3 METHODOLOGIES, PROCESS AND DESIGN PRINCIPLES

This section explores the methods and processes that have helped shape the project in conjunction with the design principles that has been laid out for this project.

3.1 User Centred Design

User Centred Design (UCD) is a framework that helps understand the requirements of the user and use that information to feedback to the design and development. UCD is best implemented in iterative design and development phases. Hartson and Pyla (2012) explains how UCD can be used in creating a rich and interactive system. The key philosophy of user centred design is to understand the user by various techniques. The key questions that UCD prompts to explore includes, who are the users, what are their goals, what are their experience levels, what information the users might need.

An introspection into these questions posed by UCD helps create a system that is useful for the target audience. This project utilises UCD framework to explore the experience and evaluate each of the artefacts generated by each iterative phase.

3.2 Iterative, Agile Design and Development

Iterative development and design help to develop quickly and test the designs. Feedback from each of these phase of development and design strategy, contributed to pivot quickly, ideate and enhance problematic areas. This approach is immensely valued as it helped validate assumptions regarding materials, design and how the shape display would work. In some cases, these assumptions proved wrong, and the methodology demonstrated to be nimble enough to accommodate for these failures. The book by Highsmith (2009) explores key concepts of Agile and Iterative strategies.

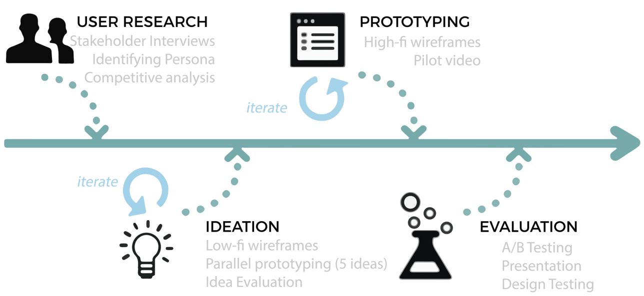

Figure 6. A typical framework for how User Centred Design would work in an Iterative process

A major differentiator in modern technology organisations is agile development strategy. This methodology introduces the concept of Minimum Viable Product (MVP). This project emphasised the use of an MVP for each of the iteration phases so that risk of failure could be minimised. In a project like this it is important to minimise failures and to have the ability to showcase the progress at any given stage in concrete steps of progress towards the end goal. It is to be noted that iterative design goes hand in hand with agile development strategy thereby maximising the impact of these two techniques.

Since this project was envisioned to be a key development project where there was no prior implementation easily available to perform user tests, it was essential to use expert review at each phase of the development. It was possible to conduct user studies after the final phase of the design and development cycle.

3.3 Design Principles

This project encapsulates certain ideologies to create a unique shape display system. This section explores these factors and explains why they are the chosen factors. Factors of design that define how the shape display would work, designing a low cost display, and the use of open source hardware and software.

3.3.1 Factors for Design

The factors chosen for design is essential for this project. It defines how this shape display exploratory project stands out with its unique features among the other displays explored in literature.

High Resolution : Most shape displays explored in literature has a resolution lower than 13*x*13. The project aims to explore resolutions from 20*x*20 to 96*x*62.

Display Density : The project seeks to achieve high display densities by using compact designs, effective packing of display elements and by using smaller display elements.

Physically Manipulatable : For this project it is aimed to have a shape display that is easily physically manipulatable and have easier access to explore the shape by enabling easy handling of the display.

Size Factor : The project intends to be easily physically manipulatable, and easily handled, which would put a constraint on the size of the shape display to a size that can be carried easily by hand.

Actuation & Speed : The shape display must be able to display any shape within reasonable speed, i.e. low frequency updates but facilitate easy update methods by providing suitable actuation methods.

Keeping the Costs Low : The shape display developed by this project needs to be accessible by researchers constrained by a budget. So this project was challenged to have a design that would keep the entire cost of actuation and shape display unit minimal. *Table 3* reveals the bill of materials for *phase 3* of this project.

Open Source : The project aims to use as much open source technologies in both hardware as well as software. Open source software and designs are typically free. S. Weber (2004) claims that open source helps to reduce costs of manufacturing as well as development by pooling in resources from contributors across the world. Additionally open source technology allowed us to tweak and manipulate several components to suit the needs of the project, which many not be a natural or legal task in closed source systems.

4 PROTOTYPES

This section explores in detail the development of actuation methods, locking system that enabled tangible interaction and subsequently the evolution of control software used for various actuation methods.

As mentioned in the design process *(Section 3)*, the project was executed in three key phases. Each phase had a different focus on various segments of the prototype.

Phases	Actuation			Design		Locking Mechanism			Software		
	Tech	**Method**	**Actuator**	**Resolution**	**Density**	**Type**	**Material**	**Design**	**Platform**	**Language**	**Library**
1	Magnet	Pull	*Piccolo*	96 x 62	16.30 PPI	Brick	-	-	Arduino	C/C++	*Piccolo* Lib
2	-	-	-	6 x 6	8.21 PPI	Brick	Several	Various	-	-	-
3	Physical	Push	Modified 3*D* printer	20 x 20	7.12 PPI	Linear	Cork	Sandwiched	Marlin	JavaScript	NodeJS

Table 4. Exploring various factors and its focus in iterative phases of prototype development and implementation.

Items	Spec. / Qty	Price
Materials		
Acrylic Sheets	3mm	£6
Corkboard	3mm	£9
Plywood	3mm	£8
Electronics & Components		
Electromagnet	1unit	£4.90
Aruduino	1unit	£15.20
Actuators		
Piccolo	1 unit	£0
Hictop	1 unit	£250
	Bill of Materials	**£293.10**

Table 3. Bill of Materials for 1 unit of Shape Display including the actuation mechanism either push or pull type. The exact cost would be lesser than what is shown in the table depending upon the chosen actuator and actuation mechanism

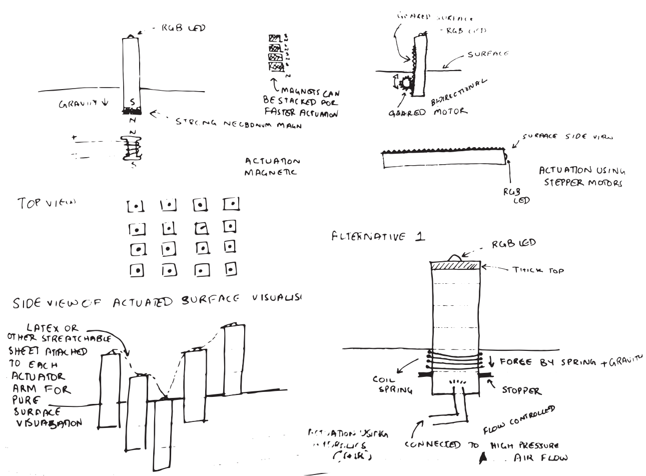

Figure 7. Early sketches exploring potential actuation mechanisms, larger version is attached in *appendix 9.2*

Table 4 summarises the various approaches towards different factors of the prototypes in each phase. There exists a focus on each of these factors in each phase. *Phase 1* targeted on the pull based actuation with magnets, whereas *Phase 2* was set up to explore various locking mechanisms and their effectiveness. *Phase 3* was conducted to gather together the best learnings from the previous phases to create a robust implementation based on an improved actuation with a solid locking mechanism. Additionally it is to be noted that the design has been iteratively explored and modified in each phase based on the insights from the previous phases.

4.1 Actuation Mechanisms

Literature explores the use of various actuation methods like Shape Memory Alloy (SMA), motors, pneumatic systems, piezo ceramics, and hydraulics and in some cases a combination of these methods.

One of the unifying concepts of the actuation mechanisms explored is that, the techniques use a variation of *pushing* the display elements. This lead us to study the potential of using *pulling* mechanisms and its relative merits. In this project, we explored two main concepts of actuation. One is to use magnetic fields created by electromagnets to actuate the display elements by *pulling* and second is to use the more traditional *push* mechanism by physical contact of the display element by the actuator.

Given that one of the key objectives of this project is to create a low cost shape display, it was necessitated to have one actuator for all the display elements on the display. Potentially in the future it might be possible to create a system with more than one actuator for a portion of the display by employing a divide and conquer strategy. This could potentially improve the speed of rendering.

4.1.1 Magnetic Actuation

To explore the realm of *pull* type actuation the first intuitive mechanism that can be thought of is the use of magnetic attraction. This version of the project used an Electric lifting magnet with a holding force of $25N/5.6lbs$. This field was focussed onto a precise pinpoint using a conical design as shown in the figure. This helped to focus the magnetic field to a very fine described point to pick up a display element of the shape display from a high density display of around $16.30PPI$[6].

[6] Though PPI stands for Pixels per Inch, in this case it is equivalent to the number of display elements per inch. The same unit is used to minimize confusion introduced by a new metric.

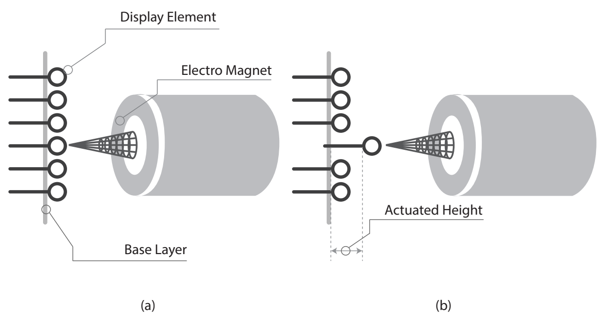

Figure 8. Schematic for a Magnetic Actuation System
(a) Positioning for actuation
(b) Actuation by electromagnet for a predefined height

It was useful to exploit the level of magnetism that is proportional to the voltage applied to the electromagnet. This gave the designer of the shape display the opportunity to utilise higher magnetic strengths for pulling multiple display elements at the same time. Given precise control of the voltage, it would be possible to pick several display elements to a particular height, drop the voltage thereby placing most of the picked display elements and continue further by actuating a single display element. This can be used to increase the speed of the system while rendering flat surfaces at a set displacement. This concept is illustrated in *figure 8*. *Figure 10* illustrates the system actuating a single display element, whereas *figure 9* depicts multiple actuations in the same instance.

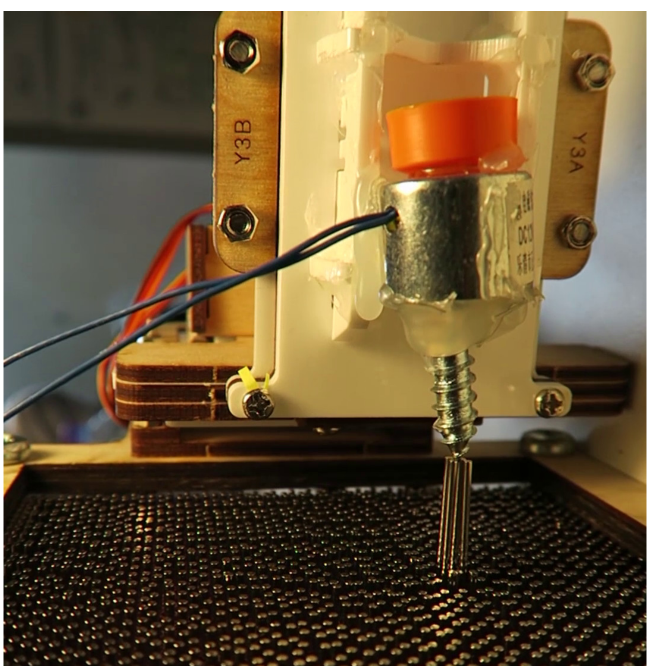

Figure 9. Working prototype of Magnetic Actuation working on multiple display elements at a time

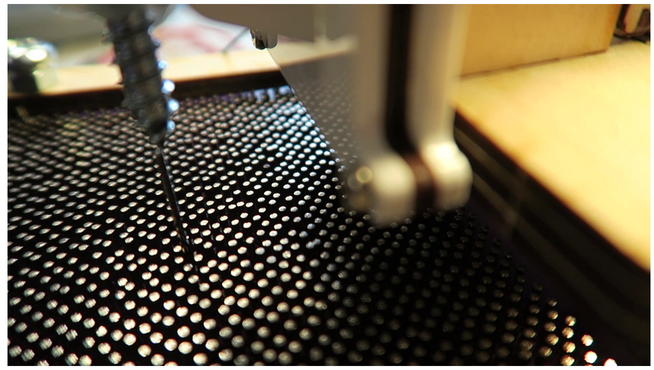

Figure 10. Working prototype of Magnetic Actuation

Magnetic actuation opens up a whole new arena of potential actuation mechanisms that have not previously been explored. There exists a potential for using magnetic repulsion to use it for *push* type actuation as well. However, this is challenging as it would require greater precision while initiating the *push* action. Not only would it require finer location accuracy for the actuation, but precise voltage control would also be of prime importance.

4.1.2 Physical Actuation

Physical actuation of individual display elements is a well explored method for shape displays. It can be considered as a traditional method for actuation for shape displays, which is robust and fail safe.

In phase three of this project, a physical actuator was designed for the display. The actuator was a solid piece of metal shaped into the right dimensions for it to accurately target one display element at a time and not to disturb neighbouring elements. There was only one actuator for the entire display unit.

The implementation of the actuator performs a scanline type of process, in which each line is passed through, and each element actuated to the right height as determined by the input before moving onto the next line of elements.

The key concept of this type of physical actuation is to ensure a proper contact with the surface of the display element and to ensure that this contact is maintained till the actuation height is achieved. Tweaks in design had to be made to allow for the natural sag that might appear in the displays either due to spacing of layers, gravity or by fabricating the display for higher tolerances for placement of the display elements. This resulted in designing the actuator that was large enough to endure the tolerance of the natural sag but at the same time small enough to not disturb neighbouring elements.

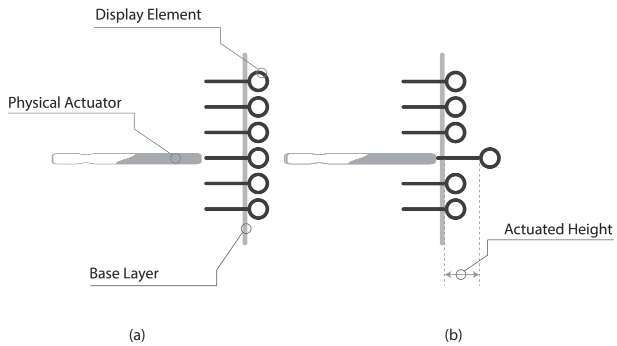

Figure 11. Schematic of physical actuator

4.1.3 Choosing the right Actuator

Physical actuators provide a high degree of repeatable accuracy and lowered the total cost by eliminating the requirement of magnets. This was one of the key reasons for choosing physical actuators for the *Phase 3* implementation.

To use magnetic actuators effectively, we first have to solve the following design problems. For example after numerous experiments with magnetic actuation it was found that the display elements exhibited a tiny amount of residual magnetism which caused actuation inaccuracies in eventual actuation of these elements. Residual magnetism and its challenges could be addressed by focussing on the material used, specifically the alloys and the metallurgical properties of the steel used for the display element. This was however beyond the scope of this project, and it was decided to forge ahead with proven contact based physical actuation.

4.2 Computerised Numerical Controllers (CNC)

Numerical control or Computerised Numerical Control[7] are precision automated machines operated by control commands that are sent via a storage medium or network. In this project, we explored two numerical controllers. The first phase of the project explored the use of *Piccolo*[8], the tiny CNC-bot, which is a pocket sized open source CNC. During the final phase of the project, we appropriated the use of a high accuracy *HICTOP Prusa i3*[9] 3*D* printer.

4.2.1 Piccolo

Piccolo is an open source project that is flexible and can be used to mount different tools on it. *Piccolo* was used to mount different types of actuators. This proved to be a platform to initiate experiments for this project. By using the Piccolo CNC platform, it was possible to explore the actuation technologies for shape displays early on, in the project design cycle. A special mount was designed for it to be used in conjunction with a shape display. See *figure 12* for the design and the pictures as to how the *Piccolo* was mounted on the display.

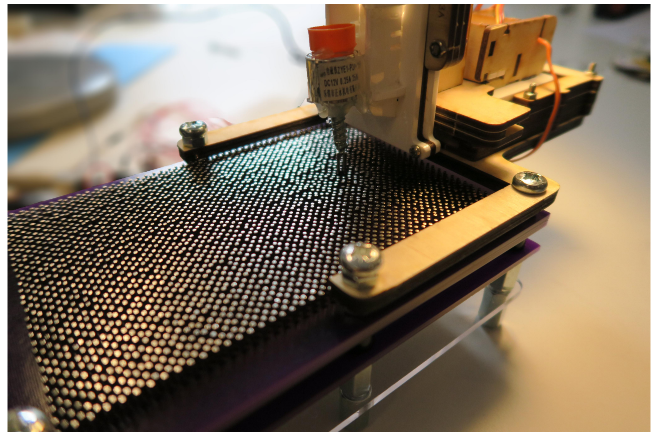

Figure 12. *Piccolo* mounted on a 96*x*62 shape display with magnetic actuation.

Advantages of *Piccolo* were overshadowed by its downsides; several challenges were faced while using *Piccolo*, including it not being able to handle its weight and having its gears slip. Additional concerns of *Piccolo* were the choice of recommended materials for digital fabrication. The selection of plywood, specifically in the recommended thickness, was too flexible. In *Piccolo* this property inevitably leads to inaccuracies during its operation. The technical evaluation of the *Piccolo* platform, however, made the following limitations apparent. The device was not easily scalable to a larger target area. A scaled version of *Piccolo* often meant a complete redesign. Though *Piccolo* had its share of disadvantages, we found that it was a valuable tool to kick start the experiments in shape displays.

4.2.2 3D Printer as a CNC

Given the Piccolo platform's limitations, it was important to explore other low cost CNC machines that offered higher accuracy. Therefore, we explored the available options and procured the *HICTOP Prusa i3*, DIY 3*D* printer. The device offered a high accuracy platform for CNC with an accuracy of about 0.1*mm*. In addition to the high accuracy of the device, it offered a much larger target area of operation. The workable area of this device is set at 2700*x*2000*x*1700*mm*, which was large enough for the actuation of our envisioned shape display.

This machine works on Marlin[10], a firmware for Arduino

[7] https://en.wikipedia.org/wiki/Numerical_control
[8] http://piccolo.cc/
[9] http://www.hic3dprinter.com/productshow.asp?ArticleID=0&id=15&cid=001
[10] http://reprap.org/wiki/Marlin

platform used in 3*D* printers. Marlin works over grbl[11] a *gcode* parser enabling the user to send high level instructions for it to accurately operate the Numerical control. *gcode* has been standardized as *RS-274* and *ISO 6983*.[12] Unlike *Piccolo*, this machine offered a much higher quality and precise control to operate the CNC. Custom parts were designed to mount the actuators on this machine though the preconfigured component list offers only 3*D* printing attachments. See *figure 13* below for the design and the pictures for how the shape display was mounted on the 3*D* printer.

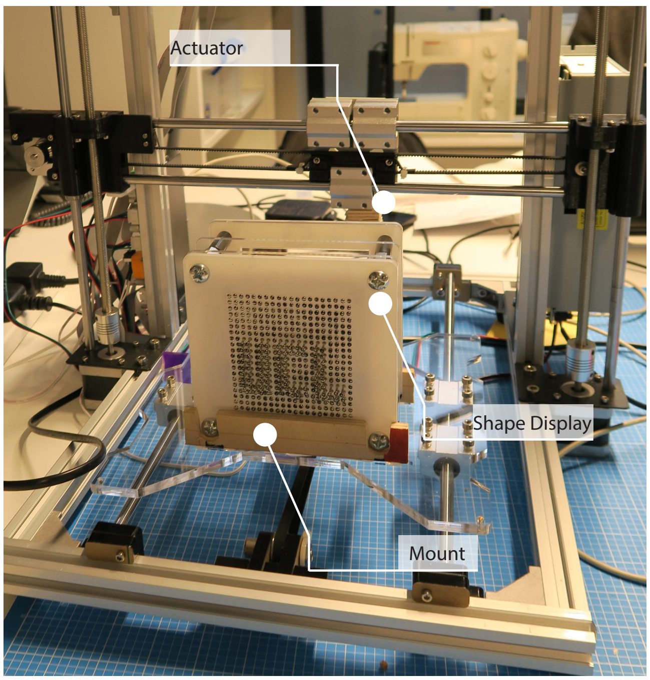

Figure 13. Shape display mounted on 3*D* printer used as a CNC machine

Initial experiments with the device showed that this machine could be configured to perform at high speed for operations in the X and Y axes whereas a significantly lower performance speed was available in the Z-axis. Given this limitation a tweak was performed to transform the axes in the 3*D* printer to correspond to different axes for the shape display. The details of this transformation is described in the *table 5*. This along with the scanline technique used for actuation minimized the impact of the slower speed along the Z axis.

A mount was produced on the *base platform* of the 3*D* printer so that it was easy to mount the display onto the machine and for easy removal once the shape was rendered on it. Particular attention ensured that the mount was easy to use and assured that the calibration of the system remained as initially designed. A poor mounting mechanism can easily cause a distorted shape to be rendered on the shape display.

CNC Axis	Shape Display Axis
X	X
Y	Z
Z	Y

Table 5. Axis transformations for the CNC axes as compared to that of the Shape Display axes to improve performance.

4.3 Locking Mechanisms

The locking mechanism in a shape display provides rigidity to the actuated display elements. Once a lock is engaged a user can exert pressure on the actuated surfaces and potentially manipulate the surfaces as required. To create a usable shape display, it was important to implement a locking mechanism. This was an intricate design and implementation problem to solve for the shape display.

The project explored two main ideas of creating a locking mechanism and explored several materials to understand the limitations and to narrow down plausible materials for future designs. These mechanisms are explored in detail in the following sections.

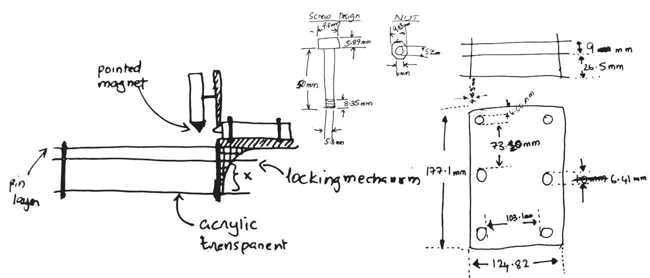

Figure 14. Initial sketches of locking mechanism and dimensions for design. Sketching proved to be an ideating tool, sketching concepts from Greenberg, Carpendale, Buxton, and Marquardt (2012) were used. Larger version of this sketch is available in *appendix 9.3*

4.3.1 On-Demand Friction Lock

On-Demand friction lock approach to locking the display elements in place involved creating a mechanical design that increased the friction on the display elements as and when required. The design involved creating a locking layer that created tension in the system thereby increasing the friction. *Figure 15* explores how this locking layer creates on-demand friction for the display element.

[11] https://github.com/grbl/grbl

[12] http://www.iso.org/iso/catalogue_detail.htm?csnumber=34608

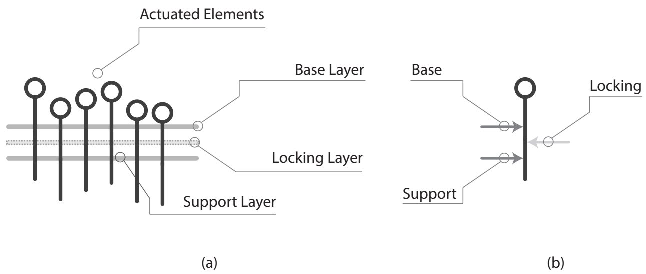

Figure 15. On-Demand Friction Lock
(a) Arrangement of Shape Display Layers
(b) Illustrates the forces working on a display element.

One of the first discoveries of using On-Demand Friction lock was how the locking layer was rendered ineffective due to the tolerances built into the brick layout for the display elements. A brick type layout caused the forces in the system to be distributed unevenly, accordingly creating a partial lock for part of the shape display elements and leaving the rest of the display elements unlocked.

The design was iteratively improved to explore the effectiveness of the locking layer in a linear layout of display elements. Although the linear layout of display elements increased the efficiency of the locking layer, it was not enough to create a useful, tangible shape display.

The next step was to explore different materials for the locking layer to improve the On-Demand Friction Lock system. The potential use of various materials were explored from diverse plastics, plywood of different thicknesses, foam core, foam board, corkboard, rubber, vulcanized rubber to paper. Each material showcased diverse performance factors for the effectiveness of the locking layer. *Table 6* showcases the effectiveness of the locking layer by varying the materials used.

Initial experiments showcased that flexing the locking layer offered a higher effectiveness of the On-Demand Friction layer. Though this phenomenon is not fully explored, it is hypothesised that this is due to the higher friction offered by the layer, which are not blocked by display elements previously locked. This warrants a further detailed study of this aspect of the locking layer.

4.3.2 Permanent Sandwiched Friction Layer

Exploring the effectiveness of On-Demand Friction Lock mechanism it was evident that without identifying the right material it would prove difficult to use the locking layer method.

To forge ahead to create a useable and tangible shape display, it was decided to explore different methods. It was perceptive to create an always on high friction shape display so that the actuated display elements are at desired levels to create the contour of the shape.

Material Used	Thickness	Locked %
Plywood	1 mm	25
	3 mm	20
	5 mm	15
Card Stock	210 gsm	25
	580 micron	25
PVC foamed ‘Palight’	1 mm	20
Plexiglass	0.5 mm	N/A
Polyprop	0.8 mm	N/A
Vulcanised Rubber	2 mm	40
Eco Friendly Rubber	2 mm	40
Corkboard	2 mm	50 - 60
Gerprint	800 micron	N/A
Acrylic	3 mm	10
Foamcore	3 mm	40
Foam	5-6 mm	55
Neoprene Sheet	1 mm	30

Table 6. Material exploration for On-Demand Friction Lock layer. Locked % is estimated.

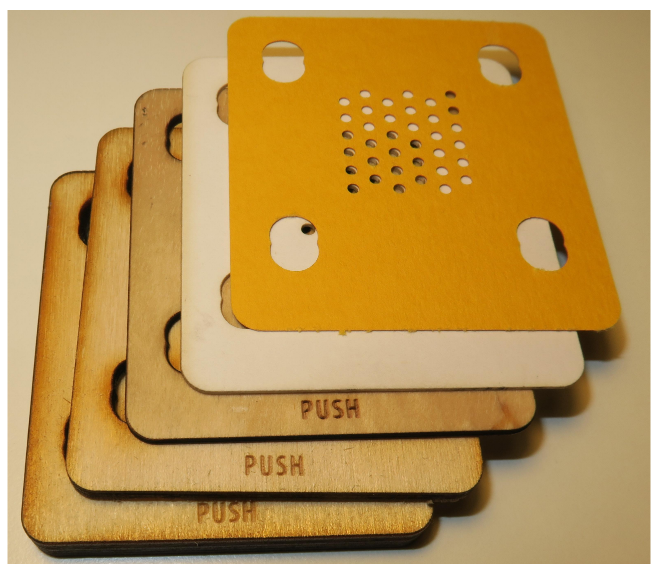

Figure 16. Samples of On Demand Friction Locking Layer fabricated from different materials. Image of other materials are included in *appendix 9.5*

A high friction shape display offers the convenience of creating a shape display that can be contoured by hand at any stage of the display rendering, thereby providing a mechanism for input for the shape display.

Different materials offer different amounts of friction based on the ability of the materials to retain its original shape after being stretched at various distances. The initial contenders for this Sandwiched Friction layer included rubber, foam and corkboard.

After preliminary exploratory experiments, it was found that corkboard offered the right amount of resistance, along with the right amount of freedom to move the display elements to the desired actuated positions. Other materials were either of higher or lower resistance than what was required by the Shape Display.

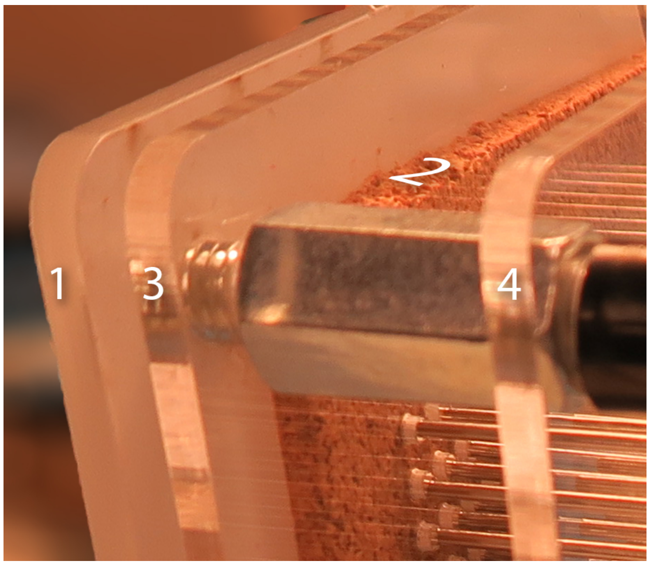

Figure 17. Sandwiched Friction Layer installed in a shape display. The corkboard based sandwich layer (2) is installed between the base layer (1) and support layer (3)

Sandwiched Friction layer offered two key advantages as compared to the On-Demand Friction lock method. The On-Demand Friction layer due to the nature that the friction layer may not be active at all points during actuation, thereby necessitating a protective layer that prevents the display elements from falling off from the shape display. The other main advantage is that the shape display can be run at a greater speed for the fact that the sandwiched friction layer contributes higher resistance thereby reducing unwanted motion induced displacement of previously actuated display elements.

Sandwiched Friction Layer offers a constant amount of friction to all the display elements at the same time. It would offer higher flexibility for the shape display if the friction layer offered variable friction, specifically if the friction level could be controlled at specific locations of the shape display.

Currently, the only way to perform this on this version of the shape display is to replace the material of the Sandwiched Friction Layer. Use of neoprene foam offers the least resistance to rubber offering the highest.

The layout of the friction layer within the other layers of the shape display leads to its name, Sandwiched Friction Layer.

4.4 Design

The shape display design has been iteratively advanced. From the design principles, the key was to pack the highest display element density within a display. For this reason, there were two main types of designs that were fabricated for the shape display, the linear shape display and the brick type shape display.

4.4.1 Design Types

Two formats for laying out the display elements in a shape display were designed. The first type is *Linear Design*. Linear type design is a straight forward design concept where the display elements are arranged in a linear fashion. This was elementary to fabricate and implement. The main advantage of a linear design is that it enabled easier transfer of forces in an On-Demand Friction layer type locking mechanism. Although the design proved to be simple to implement, the pixel density of such a display was fairly lower. This kind of design was useful to experiment various types of actuators and CNCs.

The second type of design is called *Brick Type*; the name is derived from the style used for brickwork while building a structure. Brick type design allowed us to pack a high density display with 5952 display elements packed at a density of about $16.30 PPI$. The highest density that could be achieved with the chosen display element.

Brick type design resulted in a zig-zagged contour at the edges of the display, but this outweighed the display density achieved. Brick type design although, offering a higher display density it caused hindrance in the performance of the On-Demand Friction Lock mechanism. This could be attributed to the fact that the brick type design caused the forces of the locking layer to be distributed thereby reducing the friction induced.

4.4.2 Designs Across Phases

In agreement with the pre-defined design principles, one goal was to increase the display pixel density as high as possible. Hence in *Phase 1* of the project it was decided to implement the Brick Type Design with the highest density for the given display element size.

It is to be noted that fabricating these brick type design on an Acrylic base sheet was time consuming at about $1h50m$ per layer of the design. The heat generated during fabrication was high enough to deform the fabricated layer. This warping of the fabricated layer was fixed by heating the fabricated

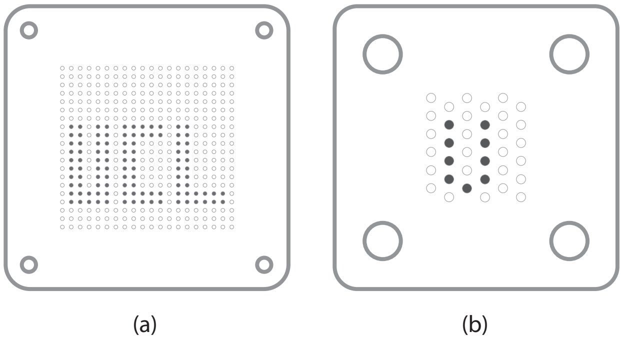

Figure 18. Shape display designs
(a) A $20x20$ Linear Type Design
(b) A $6x6$ Brick Type Design
Note that even in lower resolution brick type design is more adept at displaying curves

layer no more than 150^oC and slowly cooling it to room temperature under pressure using a Heat Press Machine.

Phase 2 being an exploratory phase, the main focus was to develop and create a successful locking mechanism. This minimized the demand for high resolution for this phase. Hence for this phase the design was shrunk down to smaller shape display arrays ranging from $1x1$, $4x4$ and $6x6$. This was implemented using the brick type design.

Phase 3 of the project chose linear type design for the shape display. Given the nature of the design, it was not possible to pack a higher resolution for this version of the display. It was chosen to go for a modest $20x20$ display with a density of $7.12PPI$. Though it is to be noted that the resolution and the pixel density is higher than that of the shape displays discussed in the literature that has a maximum resolution of $13x13$.

4.4.3 Layering

The shape displays were constructed in layers. The basic construction used three layers, cover layer, base layer and support layer. These layers were spaced in predetermined spacing with respect to the length of the display element.

The three layer system was enhanced with one more layer, either an On-Demand Friction Layer or a Sandwiched Friction Layer based on the locking system used for the shape display.

In case of Sandwiched Friction Layer, it was found that the system was stable enough without the cover layer, and this cover layer was removed to support direct interaction with the shape display. Eventually, a modified version of the Sandwiched Friction Layer based Shape display was created with *five* layers, base layer, sandwiched friction layer, immediate support layer, spaced support layer and a mounting layer.

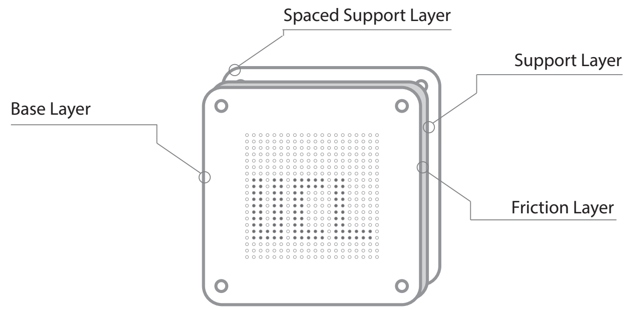

Figure 19. Typical layering arrangement with a sandwiched friction layer

Though a mounting layer was not truly necessary it gave the system additional robustness and solid mounting platform for the shape display to be actuated.

4.5 Fabrication & Construction

Fabrication of the design was carried out at the Institute of Making, using a Laser cutter with $50w$ laser, the work area for fabrication is $610x457x229mm$. The fabrication time varied based on the size and design used. The most complex design was the brick type design with a resolution of $96x62$, which consumed approximately $1h50m$ per layer. The design required three layers to be fabricated. Other designs took lesser time for fabrication. Although majority of the time was involved in fabricating the shape display, some limited amount of time was spent on fabricating parts for *Piccolo* and the $3D$ printers for their use in respective phases.

Figure 20. $1x1$ Shape display for *phase 2* of the project, one of the many versions of shape displays fabricated for the project.

Phase 2 of the project required to explore the use of various materials. Preset configurations for laser cutter were available for different materials that could not be directly used. Either the power setting was too low, causing the laser not to fully cut through, or the power was set too high, melting or burning the areas adjacent to the cut. A calibration test pattern was cut several times to ensure that a perfect cut and engraving was achieved. It is noted that some materials like *polyprop* was not usable in laser cutting, as the material tend to melt and reform as soon as the cut was finished thereby rendering an unusable fabrication.

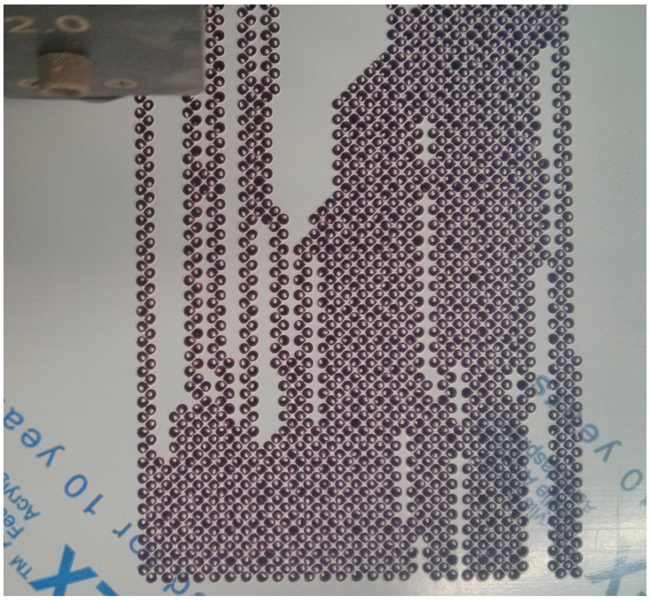

Figure 21. Fabrication using a laser cutter

In some cases, the materials warped due to the intense heat built up within the material. This was most prevalent in plastics, specifically acrylic. This warping was fixed using a heat press.

Beyond the use of laser cutter, manual fabrication tasks were performed that involved cutting, shaping, sanding and gluing plywood, acrylic and other materials to create mounts for the shape display. Similar manual process were employed to create the mount for the actuators.

Construction can be broadly categorized into two sections. First is the construction of the numerical controls including *Piccolo* and the 3*D* printer. Second is the construction of the shape displays. In accordance with the requirements of each build of the shape display, it was mounted on either *four* or *six* mounting bolts of *M*6 dimension. The length of the mounting screws were dependent on the number of layers and the length of spacers used. This was either 50mm for the versions with fewer layers or 70*mm* for the displays with more layers.

Once the mount was prepared the display elements were mounted. In all phases of this project, the same display elements were used. The display elements are steel pins that measured 1.4*mm* in diameter, and 30*mm* in length, one end of the display element was a pin head that prevented it from passing through the base mounting layer.

Once the display elements were assembled, the layers were separated by spacers as per the layer design and then mounted with the mounting bolts. At the end of which the nuts were used to secure the assembly and increase the rigidity.

4.6 Control Software

Control software is an essential component of the shape display. The control software translates depth map source information into physical movements of the CNC units and helps in activating and deactivating the actuation mechanism. As with the evolution of the design of the shape display, the actuation methods; the control software too evolved with each iterative phase. The control software had an association with the Computerised Numerical control system that was being used. The first version was based on the *Piccolo* platform and its associated library. The later versions were built over the standard language for CNC machines, *gcode*.

4.6.1 Piccolo and PiccoloLib

The first version of the shape display utilised *Piccolo* platform. *Piccolo* is designed as a low cost CNC machine. The platform worked on Arduino, an open source computer hardware and software for building digital devices and interactive objects. The *Piccolo* platform worked on standard Arduino compatible hardware and had a library for easy implementation of code.

The initial version of the control software was developed to enable the basic functionality of the shape display system. It was limited to actuating the display elements to a predetermined height that was hardcoded within the software system. The system worked in a simplified manner. The first step was to locate the display element that was needed to be actuated, then actuate the located display element. Once this was done it could move to the next display element that needed to be actuated.

Additional explorations were conducted on this platform to leverage *Controllo*, a *Processing*[13] based application that works in conjunction with the *Piccolo* library that enables users of the system to send test patterns to *Piccolo* device. Additional features of *Controllo* allowed the users to upload SVG (Scalable Vector Graphic) format files that could be used as inputs for the shape display. An additional feature of *Controllo* allowed the users to use the mouse to create vector shapes that could be sent to *Piccolo* for expressing the vector as a shape display.

[13] https://processing.org/

4.6.2 gcode and NodeJS

In *Phase 3* of the project, it was imperative to have a higher accuracy machine. In this phase we utilised a standard 3*D* printer that was working using the *Marlin*[14] platform. Marlin is a firmware for RepRap 3*D* printers, the software that resides on the controller board and controls the input/output, voltage states, and movement of the 3*D* printer. Marlin platform implements *gcode*, which is a programming language for numerical controllers.

A server was coded that created two connections, one is for a client software to connect to the server, and the second is to send low level *gcode* instructions to the numerical controller. The design of this software was modular, and used abstractions to pass high level instructions that got converted into a string of *gcode* instructions. This level of abstraction was essential to keep the code simple and scalable.

The system architecture and the flow diagram of how instructions are processed are shown in *figure 22*. The user of the shape display is presented the user interface from the control software. Once the user selects a depth image for rendering, the user interface converts these images to high level instruction code for the core control software. The core control software based on *NodeJS*[15] converts these high level data to low level *gcode* instructions for actuation. This *gcode* instruction set is cached and passed to the numerical control that performs the actuation, rendering the shape on the shape display. This architecture is simple and easy to implement. The architecture of the system is designed to be modular in nature. This modularity helps advanced users of the system to tinker and modify different components thereby tweaking the shape display system. The system software code is available on GitHub[16] and the relevant parts are available in *appendix 9.8, 9.9 & 9.10*.

The client software was designed in HTML and JavaScript and would work on any modern browser. The interface was simple and all it required was to upload a greyscale (see *figure 23*) image of predetermined pixel dimension. The greyscale depth map is a standard representation of shapes or 3*D* information generated using any standard modelling software. This image was considered as the source image for actuation for the shape display. The client software would convert this information into pixel information, and the colour of the pixel determined the depth to which the display element would be actuated.

The system as a whole contained multiple failsafe to prevent the machine from operating in unsafe conditions. This was necessary to scale up the system from a simple *gcode* transmitter to a high level instruction parser. For example, the system would be able to accept colour images, which would be translated to greyscale before parsing it for the next level of

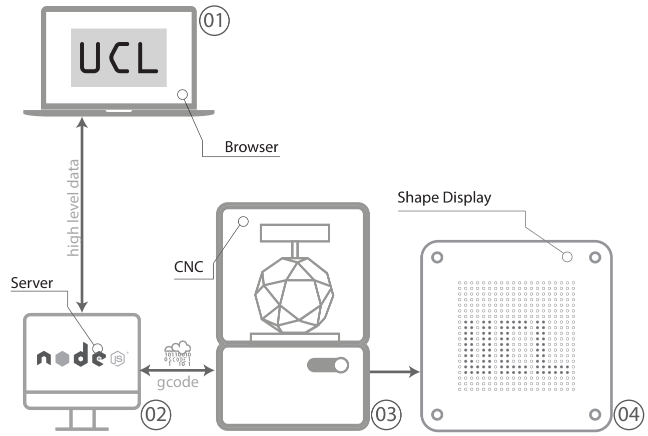

Figure 22. System Architecture, the numbers indicate the typical flow of information for a shape display actuation

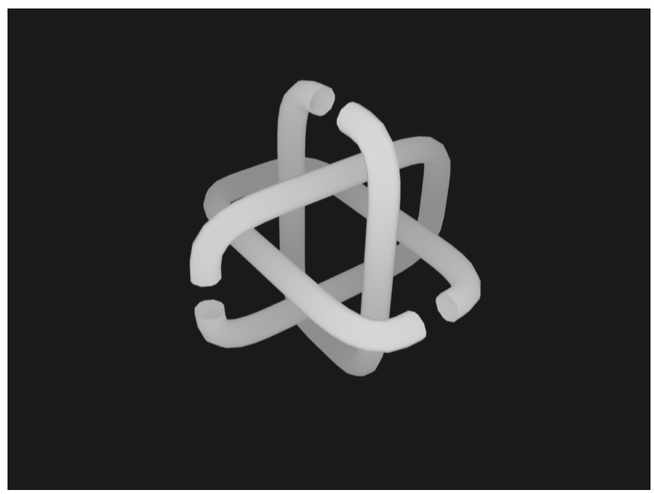

Figure 23. Example of a high resolution depthmap[17]

processing. The levels of the actuation were translated from a greyscale code of 256 levels to the levels that are representative of the shape display that is currently being actuated.

Other protection, mechanisms were integrated such that the axes of the numeric controller would not step beyond predefined boundaries to minimise mishaps.

The level of abstraction allowed the system to function at a very high level of instruction. For example if it is required to actuate the display element at position $x = 5, y = 10$ with a height of 5 units, the system had an abstract function named *pushpin* which would take in parameters of x, y and *height*. If the values were found to be within the safe limits of the

[14] http://www.marlinfirmware.org/index.php/Main_Page
[15] https://nodejs.org/en/
[16] https://github.com/sandeepzgk/ShapeDisplay
[17] Sourced from http://www.imsc.res.in/~kapil/geometry/borr/borrodepth.png

machine, it would convert them into a series of *gcode* instructions.

These instructions are passed over to the numerical controller via the serial port. Once these instructions are received the controller positions the actuation head over the global x and y coordinates, which would be different from the initial values passed to the function. After reaching the position the actuation head is activated and the display element is actuated to the desired height.

Another important aspect of the control software is the user interface. The user interface of the control software allows the user to select the shape display that is attached to their computer. Once the device is selected the user is able to select depth map images from their libraries and pass this on to the shape display by initiating the render process via the render button. *Figure 24* shows the user interface for the control software.

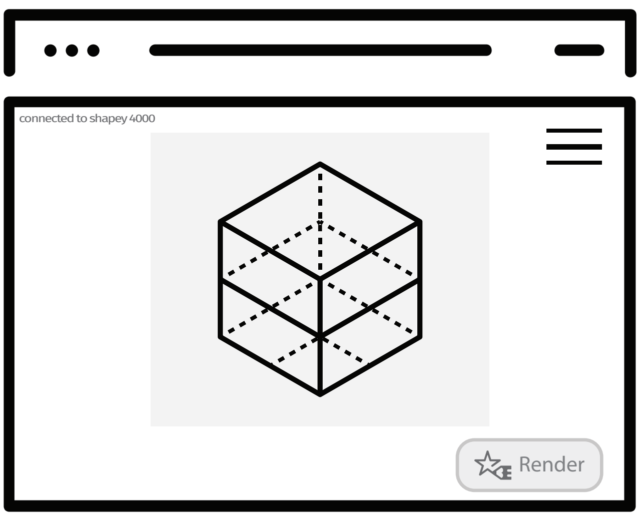

Figure 24. User Interface of the Control Software

4.6.3 Calibration

Any display system would require calibration for optimal performance. In all cases the calibration of the system was performed based on the shape display parameters. The system can be intuitively calibrated based on measurements of the shape display. Current implementation requires the calibration information to be hard coded within the server code. This could be moved to a calibration file residing outside of the code in future iterations.

One needs to input the global co-ordinates for the first display element of the shape display. Once this is fixed, the next step is to input the pitch of the display elements in both x and y axes. This is necessary for the system to target accurately all the display elements across the shape display. After the pitch information is configured in the system, it needs to understand the maximum height, which is permissible for actuation for the shape display. Once these three elements; i.e. Global coordinates of the first display element, pitch in both x & y axes, and the maximum actuation height are obtained, the system can be considered calibrated and ready for use.

The shape display needs to be reset before rendering a new shape on the display. This can be achieved either by manual resetting for physical actuation. Whereas it is possible to reset the device using the magnetic actuators by rendering in reverse.

Stage	Methods
Pre Development	Competitive Analysis
Phase 1	Expert Review and Technical Evaluation
Phase 2	Expert Review and Technical Evaluation
Phase 3	Expert Review and Technical Evaluation
Post Development	Online Survey

Table 7. Methods employed at various stages of the project

5 EVALUATION AND EXPERIENCE

User feedback is a valuable input to any iterative system to improve the technology and experience. Shape displays can be used in education for representing mathematical problems like 3*D* equations, parametric surfaces like the *torus*[18]. Tangible displays can also be used in tele-surgery to represent textures of various parts for surgeons. Given that shape displays are utilised in a multitude of use cases which varies from health care to education, it is hard to focus on certain profiles of users and iteratively improve the display mechanism. Moreover, given the fact that the system is innovative and has been in regular iterative development, it was not feasible to allocate dedicated access to the shape display system for each potential user or user groups.

Eventually, in the future it might be possible to explore the use of shape displays for a particular segment of users for a particular usage scenario. This project aims to keep the exploration as wide as possible.

The key concepts in this section are to discuss the methods utilised, and the outcome of these evaluation studies that can potentially be used in future versions of the shape display.

5.1 Method

Table 7 summarizes the different techniques used in this project.

[18]https://en.wikipedia.org/wiki/Torus

5.1.1 Competitive Analysis

Competitive analysis was the first step of the project in which various technologies were explored within shape displays. Competitive analysis gave an insight into the current state of technological advances and the use of shape displays in various fields. Usage scenarios varied from remote actuation to mapping territories displaying GIS[19] information.

During this initial analysis, this paper compared 18 different projects that showcased their work in published academic papers and other sources. Some projects did not disclose their exact nature of technology used because they were protected under military projects that are intellectual properties owned by their respective owners.

It was found that in general, most of the shape displays explored in the competitive analysis had low resolution and poor pixel density. The main actuation technologies explored were the use of servo motors, shape memory alloys or piezo-electric actuators. Some projects explored the use of supplementing the shape display by projection of images or by audio feedback. Almost all of the displays explored were large and cannot be easily moved or handled. This analysis helped to set the key design parameters including the cost factor, resolution, and potential actuation mechanisms.

5.1.2 Expert Review and Technical Evaluation

At the completion of each phase of the development, an expert walk-through was performed in which key aspects of the project was evaluated and scored. The mentors along with the author were the experts evaluating the system. The scored evaluation of various aspects of the project in both, the usability of the project along with the technical dimensions of the project helped in deciding the key focus for the next iterative phase. Jacko (2012) provided insights on how to conduct an expert review.

An evaluation matrix was created for evaluating in a consistent manner across the phases. *Table 8* shows the evaluation matrix that includes factors covering technical parameters along with usability aspects. The usability aspects of the evaluation matrix were based on heuristics by Nielsen (1999). Results of this evaluation method are listed in the table. Since this assessment is a subjective evaluation by an expert, a set of sub-factors was constructed to evaluate for each primary factor. For example, in case of the factor *software*, a score of 2 represented that, in that phase the software was not mature enough to have user input or an easier input mechanism; whereas a score of 4 represents a more sophisticated version of the software was available, which was user friendly and accessible. Another example, *error prevention* factored in error prevention in software as well as the machine by the introduction of failsafe mechanisms. In initial phases, some factors were not present hence their scores are not available.

Factors	Phase 1	Phase 2	Phase 3
User control and freedom	3	-	3
Standards	2	-	2
Error Prevention	1	-	3
Flexibility	3	-	3
Aesthetics	2	3	3
Help & Documentation	1	-	2
Speed	2	-	3
Accuracy	3	-	5
Locking	-	3	5
Resolution	5	2	3
Software	2	-	4

Table 8. Expert Review and Technical Evaluation performed across phases of the project, Note that this was based on a Likert Scale ranging from 1 to 5

During *phase 1* of the project, the key focus was on obtaining a system that would render shape display without much spotlight on speed, accuracy and standards. Whereas during *phase 2* the spotlight was shifted to locking mechanism and improving the aesthetics of the system. During the final phase of the project; *phase 3*, the concept was to bring in the sound parts of both *phase 1* and *phase 2* and to improve on them based on the iterative experience.

Future versions of technical evaluation can be performed with objective performance measurement metrics. The current set of evaluation metric is a Likert scale value from $0-5$. This although would not fully convey the intended measurements, it can quickly help find aspects of the project that needs immediate attention in the next phase.

5.1.3 Online Survey

Once the development phases were concluded for project, a formal investigation into shape displays and how it can potentially be used in various use cases, was performed. For this, an online questionnaire was launched in consultation with the book by Brace (2008). The questions were open ended questions rather than appraisal or evaluation questions.

Participants for this study were students of University College London (UCL), ages ranging from 22-35. Every participant had a background in Human Computer Interaction (HCI), which makes this online survey valuable given their background skill set. This survey can be considered as an ex-

[19] A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present all types of spatial or geographical data.

pert survey by several experts and their collective knowledge on the field. 15 participants were recruited for this study. Though the participants are experts in the field of HCI, they are not the target users for the system. This limits the validity of the data gathered from the participants.

Procedure : It was important to guide the participants and familiarise them with tangible displays and shape displays. For this reason, the first part of the questionnaire gave a quick insight about tangible displays. This was achieved by the use of short texts, information regarding what constitutes a shape display along with illustrative video demonstrations of the technologies. Two videos were included in the survey. One was a video of the current project rendering a shape display. The second video was one that was showcased of inFORM project by Follmer et al. (2013).

Design : The survey was designed to elicit responses to evaluate the *perceived* value of tangible displays, compare it with other existing technologies (like $3D$ printing, fabrication tools) and finally to explore *out of the box* ideas.

The questions used in the survey are listed below. The exact form used in the survey is available in the *appendix 9.6*.

- As a potential user of this technology, what do you think is the value of interacting with tangible elements?
- You might have seen digital fabrication tools like $3D$ printers and other sculpting tools. In your perspective what could be perceived as the advantages of tangible displays?
- There are some prototypes in large labs which showcases dynamic tangible user interfaces, which showcases different shapes or information as rapidly as you see on your screens today. In what context do you think would this be useful?
- In the future it might be possible to create tangible interfaces of the scale of nanometres, or as large as cities. What could be the potential uses of this type of tangible interfaces in scale?
- I would like to hear your creative concepts of the potential application of this technology?

The questions were intentionally framed to be open ended and exploratory in nature. This was done to gather a wide range of plausible responses from the participants.

Results : The response from various participants was positive. Some were interested in the *entertainment* aspects, for example "Game advertisement". The full result from the survey is included in *appendix 9.7*.

During analysis, certain themes emerged which can be used to potentially discuss the directions that can be aimed for the next or future versions of shape displays.

Four key themes from our analysis are health, communication, education and prototyping.

Health : Tangible elements, can potentially be used in various aspects of health, from the survey participants felt that using a shape display could potentially reduce the impact of RSI or Repetitive Strain Injury[20] for the fact that it relies on a more natural expression by hands. Future versions of nanometer scale tangible elements can probably be used to fight against diseases that are not easily curable by typical medical techniques.

Communication : Tangible bits along with shape displays has applicability in the field of communication. Experiencing remote meetings with tangible elements can potentially add higher levels of richness to the interaction by creating a multi modal communication system. Notions of using similar technologies have been brought forward to utilise haptic responses and tactical notification methods. Other ideas include the likelihood of using this technology for handling hazardous chemicals and other situations where it might be deemed dangerous for humans. This concept can be considered as the product of both Health and Communication themes.

Education : Participants proposed a set of ideas related to the field of education. The first step is to utilise the potential of rendering complex shapes of equations that cannot be easily visualised in a $2D$ environment. For example a common mathematical problem, Hill Climbing is difficult to represent in $2D$ space. Use of shape displays can help students learn the concepts involved in a more immersive manner.

Training is another aspect of education where in large shape displays can be used to create training environments that can represent various landscapes and building structures to train military personnel, fire agencies, police and other services. Such a training environment would be cost effective as it would require only a single training range that is reconfigurable to the requirement.

Prototyping : Tangible displays can be used to prototype different models rapidly. Participants ideated that shape displays could be used as a pre-rendering of $3D$ printed objects. It could be used as a tool for rapid prototyping to showcase ideas and concepts. Interactive versions of shape displays can be used as a Dynamic mould for modelling. High density and high resolution versions of shape displays can be used as an additional way of experiencing textures and show-

[20] http://www.nhs.uk/Conditions/Repetitive-strain-injury/Pages/Introduction.aspx

casing products in an e-commerce environment thereby enabling users familiarise with the product before making the purchase decision. *Quote 1* describes how it can be used in an online environment for shopping items like jewellery.

> "Online shopping. Lets say you have one of your new tangible displays with a retina-display resolution. You are on the Tiffany jewellery website and looking at necklaces. If you are going to be spending tens of thousands of pounds on a necklace or piece of jewellery wouldn't you want to see it 3-dimensionally before you buy it or even touch something resembling it? That would be pretty amazing."
>
> — Participant

Quote 1: Tangible display for online shopping

This section has focussed on the top four themes gathered from the survey. It is also important to highlight few other concepts that have been ideated by participants that cannot be directly categorised within these themes. Aspects including the plausible inclusion of the technology in rendering realistic 3*D* driving instructions in a car, military application for strategic insight into territorial information. Dynamic cities that adjust to the immediate needs of the citizen, for example, presumable ways to have roads that on demand reconfigure to match peak time demands.

These ideas constitute a whole range of possibilities of creating tangible elements of which a small part is explored within shape displays. The method of the survey helped to crowd source several interesting ideas, some of which warrants deeper investigation. Some would require a significant amount of technical progress to be made before those ideas can be realised.

6 NEXT STEPS

In this chapter, we describe next steps that can be taken to advance shape displays and tangible interaction systems. This section is divided to sub-parts that focus on Maturity Aspects and Technical Aspects.

6.1 Maturity Aspects

Any given technology goes through a *Hype Cycle* as defined by Fenn and Raskino (2013). For a successful future of tangible display, the technology must mature at a reasonable pace. Factors like Standards; Collaboration and Evaluations are necessary measures to ascertain a mature technology roadmap for tangible displays.

6.1.1 Standards

One of the major factors that can potentially contribute towards the wider popularity of tangible displays including shape displays among the general populace as well as the scientific community to push the boundaries of the technology is standardisation. Standardisation helps organisations or individuals build systems that can easily integrate and work with other components built by other vendors. This would be an ideal step for the future. Some work around the concept of standardisation has already begun, for example the work on Shape Display Shader Language (SDSL) by Weichel, Alexander, and Hardy (2015), a language for interaction with shape displays have been developed to bring common ground for software and instruction languages in this field.

This project explored the use of open source technologies, and to use standardised *gcode* for actuation. Though more work needs to be done to make abstractions of *gcode* instruction set to make the standard more open and accessible to researchers.

6.1.2 Collaboration

We utilise the concepts of jamming similar to the one described by Follmer, Leithinger, Olwal, Cheng, and Ishii (2012) to create an interface that can in the future be a programmable display element stiffness for interaction. The current implementation utilises a preset stiffness for shape changing the display, whose reconfiguration can be performed by changing the blocking or jamming layer in the design. It might be possible in future for open sharing of the work to improve and develop the world of shape displays.

6.1.3 Evaluations

Data from the survey indicates a potential for using shape displays in unique environments with specialists and experts in the field. Testing shape displays in a realistic environment and with real users for a specific usage scenario can give valuable insights to aspects of the technology that needs to be tweaked and improved.

6.2 Technology

This section focusses on the aspects of technology that can be improved iteratively to enhance the abilities of tangible shape displays. The focus of technology can be categorised to sensing or input mechanisms, actuation technology or output mechanisms, supplementary output methods and the relevant materials used.

6.2.1 Sensing

A range of sensing technologies could be used in conjunction with the shape displays. Sensing methods can act as channels for user input and interaction. The current implementation does not include any sensory mechanisms. Future iterations could use traditional input mechanisms such as capacitive touch, manipulation by sensing relative motion. Sensing can be implemented in either near range sensors like touch methods, or remote sensors like *Microsoft Kinect*, *Leap Motion* which uses gestural input from a distance. Both types of sensing mechanisms credit a proper introspection.

6.2.2 Actuating

This project has explored innovative actuation methods that have not been explored in prior literature, the magnetic actuation methods. Magnetic actuation has the potential to improve the landscape for cheaper actuation platforms. It would be valuable to continue the research and explore the potential use of magnetic push based actuations.

6.2.3 Supplementary Output Methods

Apart from the "traditional" shape actuation methods, it is feasible to add supplementary output methods, which can enhance the experience of using shape displays. These supplementary output methods could be audio, visual, or could use other senses. Overhead projection of visual information (similar to *figure 25*) onto shape displays can be used to display additional, contextual information to the shape display.

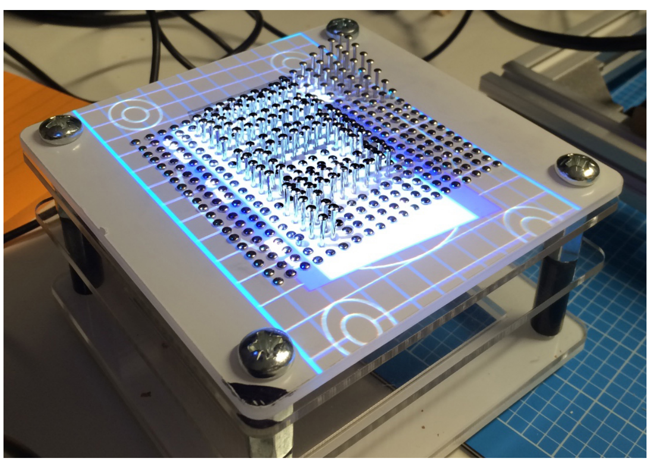

Figure 25. Additional data being projected onto an actuated shape display rendering the text "UCL"

Additional methods of using the display element to showcase colour and texture information could be valuable. This can be achieved by using fibreglass package in each of the display element (see *figure 26*). These techniques require careful implementation and testing. Testing will be valuable to judge which supplementary output methods work effectively for unique scenarios.

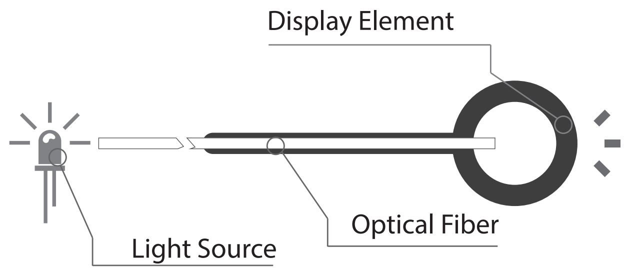

Figure 26. Representative sketch on how optical fibre can be used with a display element

6.2.4 Material Exploration

This project gave the freedom to explore materials to develop the locking mechanisms along with the examination of the different type of locking mechanisms. This was immensely valuable to learn the applicability of various materials to be used in shape displays. Composite materials offer a unique perspective of exploiting features from source materials and offering enhanced properties. Future explorations can develop on the learnings from this project and continue delving into materials including composite materials that can be used in interesting ways for tangible displays.

6.3 Limitations

Understanding the limitations of the technology helps to explore the use cases for which the technology is feasible. One of the biggest disadvantages of shape displays is its lack of ability to render overhangs. Overhangs can be described as parts of objects that are freely hanging in 3*D* space. Current technologies of shape displays cannot render overhangs. However, we can minimise the impact of smaller overhangs by using additional output methods like projected information. Apart from the general limitations of shape displays we have listed limitations unique to the implementation.

- *Single Actuator :* The current system implements a single actuator for the whole display. This can be perceived as a cost saving method as well. The impact of the single actuator causes the system to perform slower than having multiple actuators. Another impact can be the absence of dynamic display.
- *Software :* Future versions of the software can offer more functionality in terms of shape displays. For example, it could be possible to offer a user interface with an experience that allows the user to generate shapes on demand based on the information collected from 3*D* cameras or other depth sensing devices.

- *Evaluation with Real Users :* The tangible display can be improved by conducting a user study with specific scenario and usage model. This could potentially be a phase where user feedback is collected and iterated based on the collected data.

Some of the limitations of the system can be fixed in a next iteration, specifically those involving software. Limitations of mount mechanism can be fixed by using digital fabrication of the mounting mechanism. Automation process can potentially help improve the assembly process for a shape display.

Though not explored, the limitation of the single actuator can be potentially solved by using multiple actuators, in a divide and conquer technique. For example, if the design allows for four actuators, each actuator can handle rendering the partial shape in its respective quadrant. Additionally the CNC speed can be increased to actuate faster; specifically while using sandwiched friction layers, thereby positively impacting rendering time.

7 CONCLUSION

The project implemented iterative design process, in which rapid succession of concepts were made, validated, tested and tweaked for the next version. It was also possible to explore the potential use of magnetic actuation and physical actuation for the shape display. Sequential evolution of locking mechanisms has been explored by the use of unique materials, physical design of the locking system and layering for design. Similarly, the project has used open source and cost effective actuation mechanisms through the use of *Piccolo* and that of appropriating 3*D* printer as a computerised numerical control method. The design choices made throughout the project based on the design principles helped to manufacture a display that has one of the highest display densities as well as overall resolution.

This project has achieved its aim of creating a shape display that performs its basic functionalities of actuation and rendering a desired shape by utilising open source designs, tools and implementation techniques to create a cost effective tangible shape actuation display that can be used as a workbench or as a platform for further experimentations and evaluation studies. More importantly this project provides a researcher in the field of tangible shape display an *easy*, *tweakable*, *configurable* and *cost effective* platform for future development.

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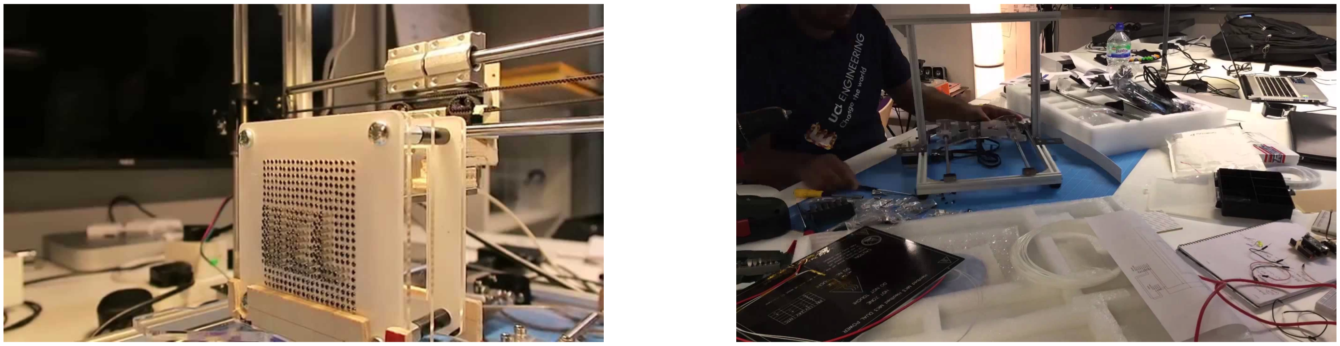
9 APPENDIX

9.1 Videos



(a) 2.5D Shape Display in Action
https://www.youtube.com/watch?v=JKKD_WTRWmU

(b) Assembling a 3D Printer
https://www.youtube.com/watch?v=ly6fyc9VZy0

Figure 27. Links to videos created for this project

9.2 Sketches: Actuation

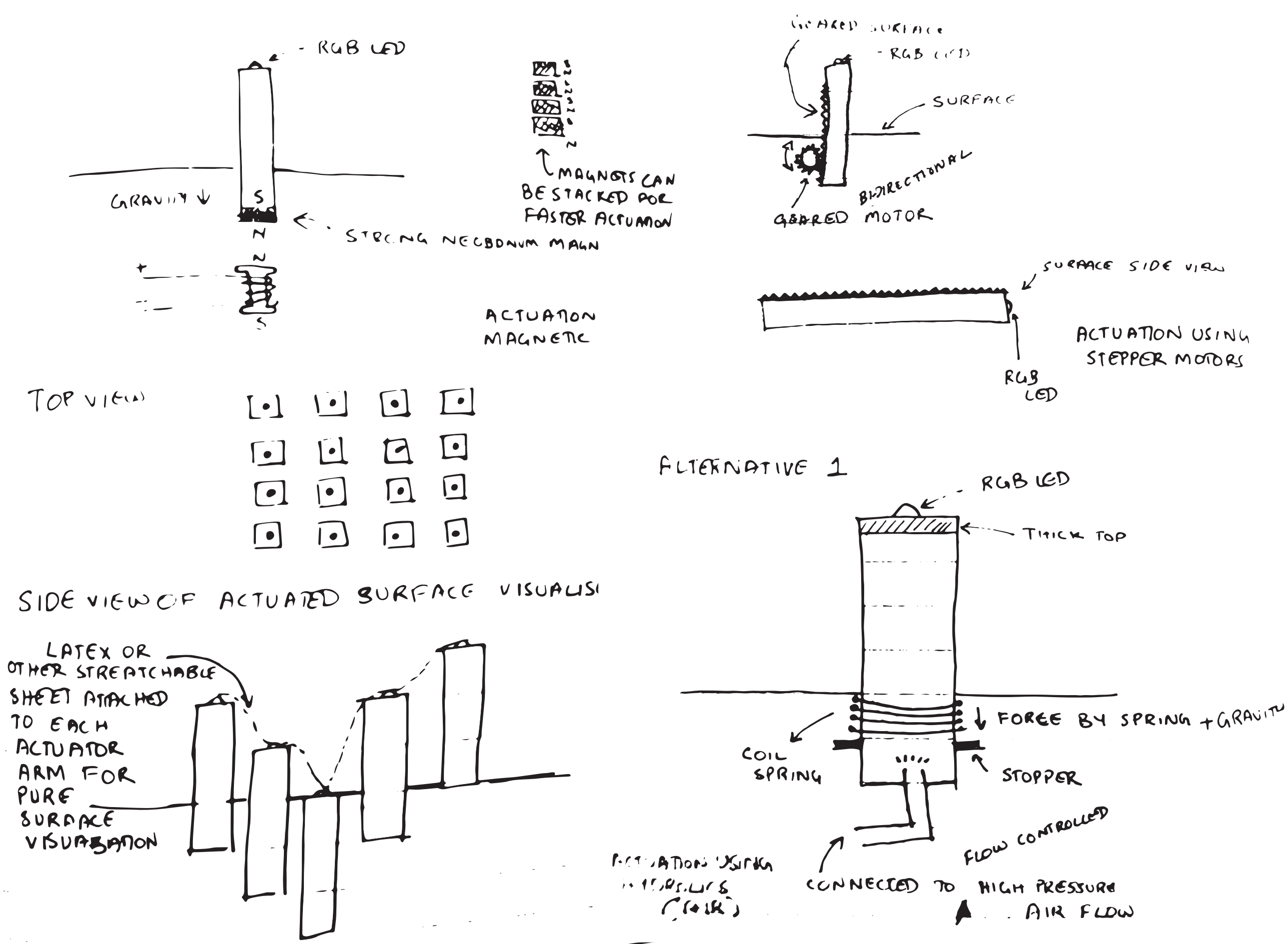


Figure 28. Early sketches exploring potential actuation mechanisms

9.3 Sketches: Locking Mechanism

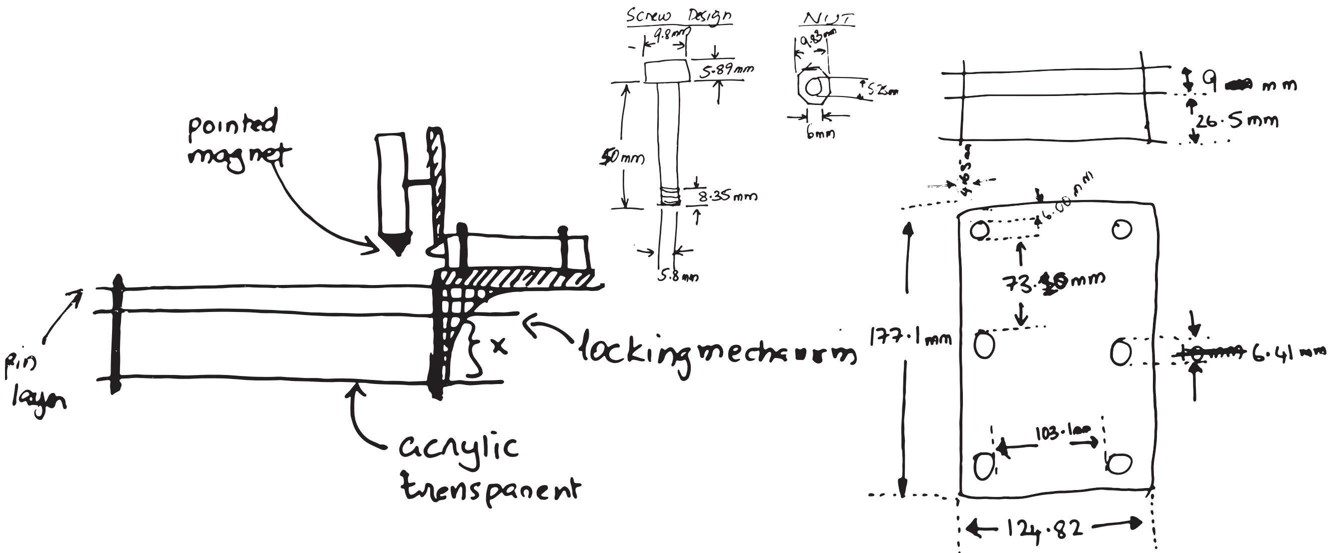
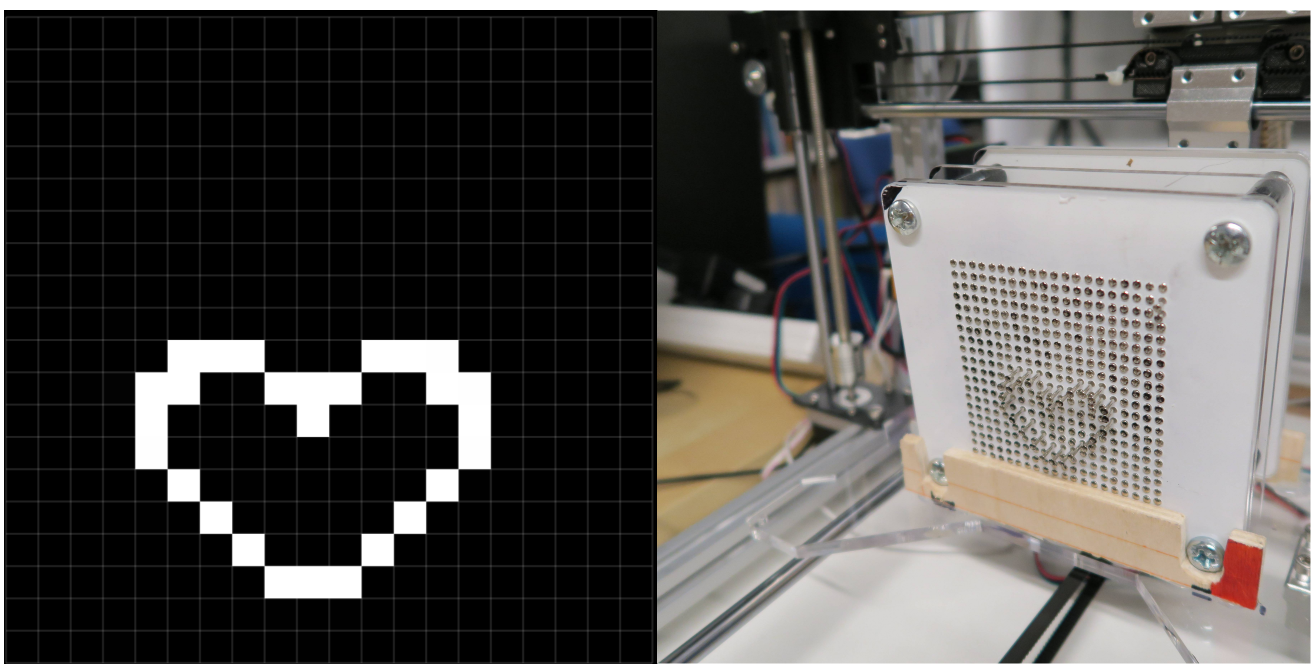


Figure 29. Intial sketches of locking mechanism

9.4 Rendering Examples

This appendix item shows the source image and the associated rendered image for 3 examples.

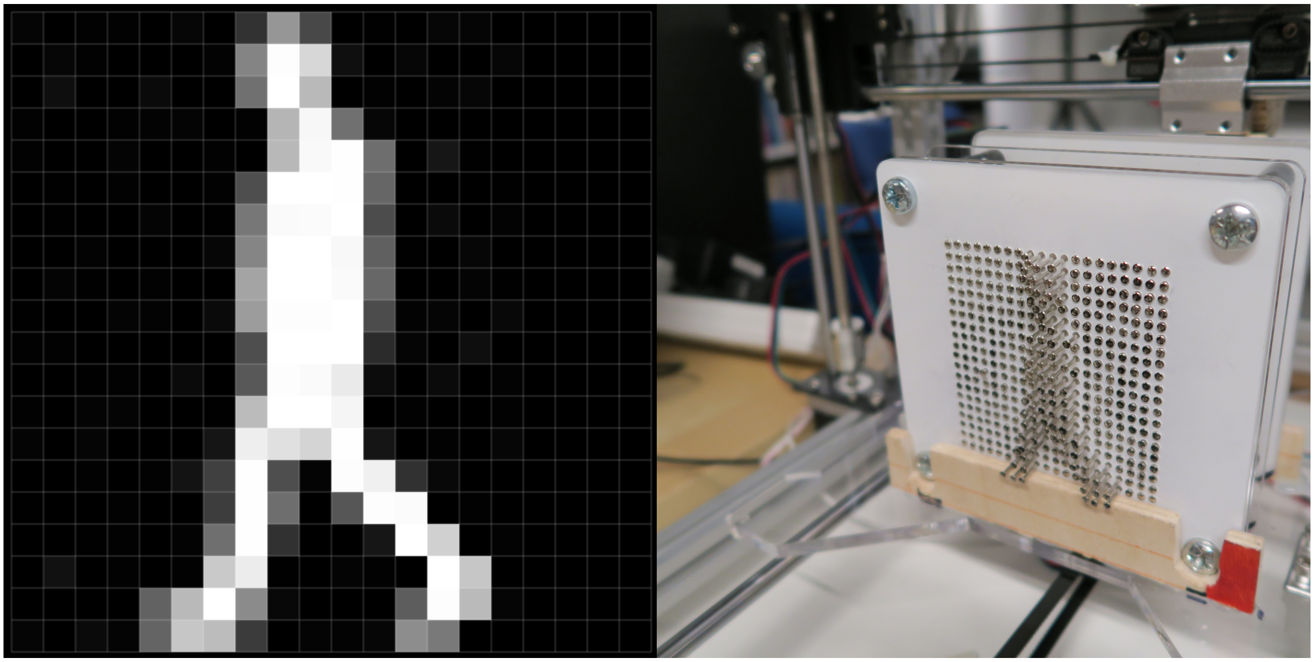
9.4.1 Heart



(a) Source image for rendering (b) Rendering on the shape display

Figure 30. Source image and the photo of final rendering of that image on the shape display

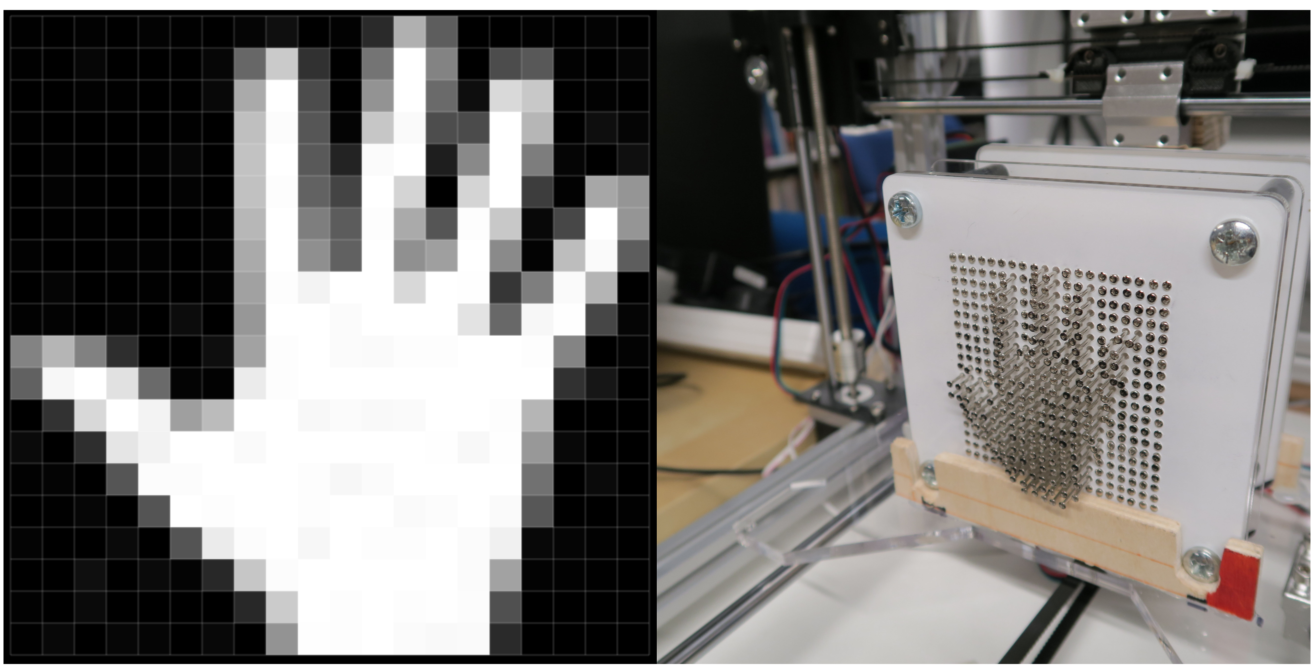
9.4.2 Walking Person



(a) Source image for rendering (b) Rendering on the shape display

Figure 31. Source image and the photo of final rendering of that image on the shape display

9.4.3 Hand



(a) Source image for rendering (b) Rendering on the shape display

Figure 32. Source image and the photo of final rendering of that image on the shape display

9.5 Material Exploration: Supplimentary Content

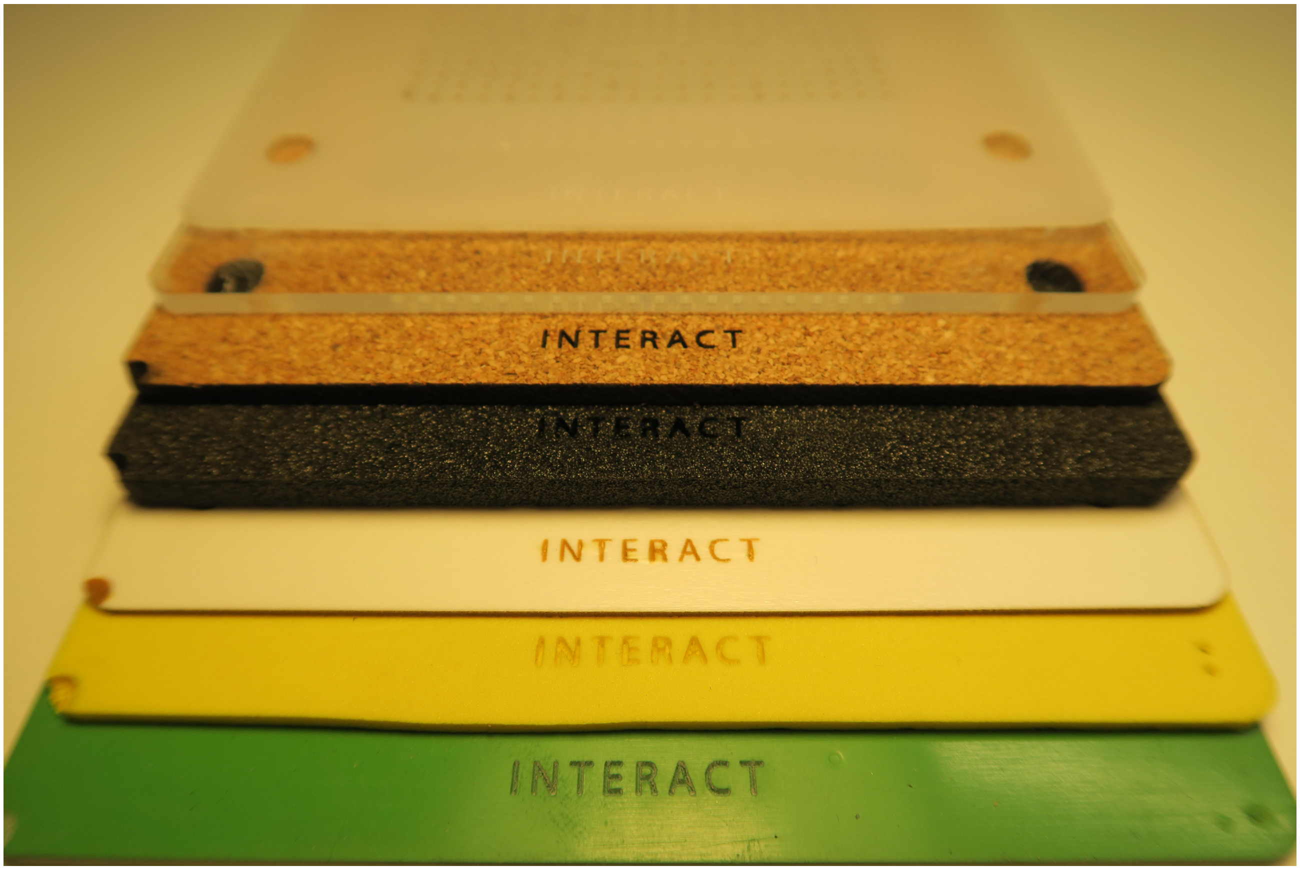


Figure 33. Image showing a range of materials explored with this project. The materials used in order *(top to bottom)*

1. Gerprint of 800micron
2. Acrylic of 3mm
3. Corkboard of 2mm
4. Foam of 5-6mm
5. PVC foamed 'Palight' of 1mm
6. Neoprene sheet of 1mm
7. Eco-friendly rubber of 2mm

9.6 Questionnaire

Experiencing Tangible User Interfaces

*Required

Background

A tangible user interface (TUI) is a user interface in which a person interacts with digital information through the physical environment. Many researchers are working on creating tangible experiences that users can physically interact with digital information.

Current Research

Tangible user interfaces are currently slow and/or expensive, and usually have very low resolution. The aim of my research is to create a tangible user interface that is cheap to produce and to make it easily accessible to the masses.

LATEST PROTOTYPE

2.5D Shape Display in Action

Here is a video of my TUI generating a shape display reading out the text "UCL", any such shape can be easily generated using the machine. The machine takes an input of an image which is represented as a shape output.

Here is another one by MIT Tangible Media Group

Amazing Technology Invented By MIT - Tangib...

Reward!

Although I am not able to offer any monetary reward for this survey, I plan to offer 5 participants of this study an opportunity to create any shape display from designs they have created in a workshop conducted after 10th of September. Those who wish to participate can leave their email addresses.

How to fill up this form?

Here are five (5) questions to understand your UNIQUE perspective of tangible user interfaces. These would be valuable feedback to start a conversation on what could be the next exciting version of tangible displays. Welcome to the future :).

Read the background, research and prototype sections, see the videos and then you are ready to go. Answer as truthfully and completely as you can. This form should not take more than 15 minutes to complete.

As a potential user of this technology, what do you think is the value of interacting with tangible elements? *

You might have seen digital fabrication tools like 3D printers and other sculpting tools. In your perspective what could be perceived as the advantages of tangible displays? *

There are some prototypes in large labs which showcases dynamic tangible user interfaces, which showcases different shapes or information as rapidly as you see on your screens today. What context do you think would this be useful? *

In the future it might be possible to create tangible interfaces of in the scale of nanometers, or as large as cities. What could be the potential uses of this type of tangible interfaces in scale? *

Any wild ideas? I would like to hear your wildest concepts of potential application of this technology? *

Go wild :)

Email address

This is an optional field, if you want to enter the raffle for the workshop to create your own tangible shape display output

Submit

Never submit passwords through Google Forms.

Powered by Google Forms

This content is neither created nor endorsed by Google.

Report Abuse - Terms of Service - Additional Terms

Figure 34. Questionnaire used for collecting responses from participants

9.7 Results

This appendix item includes raw data collected from survey, with all PII (personally identifiably information) removed and the data anonymised. Please be aware some of the responses might be candid in nature.

Question 1: As a potential user of this technology, what do you think is the value of interacting with tangible elements?

fun, it may be useful at some point for distance things, in meetings or something where you have to demonstrate/show not co-located people some sort of visual stimulus, there could probably be educational purposes, in physics teaching maybe (thinking about the ball and it's movement or things like that), rapid prototyping in design and architecture (you just quickly 'shape' something and send it on)

From personal perspective I think it will be valuable for universal design...for instance UI for the blinds or elders who is afraid of technologies. It can also be useful for communication technology, especially between families and couple.

I think the right kind of tangible elements serve two, possibly related, functions: (1) reduce cognitive load while interacting with a system but projecting a lot of it onto physical objects (2) make use of an interface easier by channeling interaction through the familiar sense of touch

Possibly less RSI as no need to click a mouse, good for people who can't hold a mouse or can't precisely position their fingers

It looks very funny and I think it could encourage people to interact with it since touch/physical interaction is part of human nature. Besides nowadays people are so used to interact via flat screen, when people see someone is interacting with something using multiple ways like press, grab or anything physically, they could simply be attracted, like a 'curious object'. And it provides another way to perceive things.

Showing 3 dimensional detail in an actual 3d space rather than rendered on a 2D screen

1. The obvious difference in feel which will lead to a section of users being dedicated users of tangible elements 2. Reduced risk of screen addiction,which would lead to people actually using tangible elements for information alone. 3. The novelty of the concept would ensure that a user would definitely buy at least one device with this technology

from what i can see, you can control something tangible from anywhere, especially it will be good for dangerous goods or something good to be remote, or not easy to access but you can manage them from distance.

Enrich the way of how you perceive your environment. It seems that the only way of interacting is through digital interfaces. With tangible ones we are able to use other senses like touch and have a complete different experience.

We live in a 3D world (well 4 dimensional if you include time) however screens are flat and 2 dimensional. There have been many attempts to give depth to things through either the use of 3D glasses or 3D screens etc which apparently make the user feel more immersed. Thinking about going to the cinema and watching something like Avatar it does make you feel like you were more part of it. Also, when creating things which are intended to be 3D, having them on screen in 2D is at times strange. Lets say you are designing something simple with a piece of CAD software and you have a sphere as part of your design. This is a circle on a 2D screen but using a tangible display it would be a sphere (or maybe half of one). Tangible displays probably help a lot with visualising 3 dimensional things which traditional screens can only do through motion (rotating the object on screen) or shading (make it seem 3D).

It can help human beings to do something asking for precision or dangerous.

As a proud graduate of Ergonomics for Design, my first thought is that it seems to eliminate a lot of repetiton from movements, and provides more variety (on the other hand, static loading seems to be a potential issue). The value compared to traditional UIs seems to me to be more in just providing a *different* alternative that is able to express data in an additional way; I wouldn't see it overwhelmingly replacing anything that we already have. Personally I would see greatest value in design applications that benefit from direct manipulation techniques. Plus you've got the argument for people with visual impairments.

It brings more entertainment to any general experience, and could make people closer to each other through the interaction.

Allows for a natural interaction with digital elements, increasing tactile input/output, depending less on visual channels. Allows for user to 'move' around and not rely on screen/2D displays. Opportunities for visually impaired users. Enhanced multi-tasking. Tactile notifications/warnings. Allows for remote interaction/manipulation.

Getting a tactile and 3d visual sense of applications, specifically in analyzing data with spatial elements. Could also be useful for collaboration and managing interactions with collaboration since physical restrictions are are automatically built in and perceived

---

Question 2: You might have seen digital fabrication tools like 3D printers and other sculpting tools. In your perspective what could be perceived as the advantages of tangible displays?

The only fact that the display is tangible and represents something is an advantage by itself, I'm not a computer that feels bits. A tangible representation says much more than something visual, in a way is more human.

I don't really see how they are comparable, but surely a tangible display is something non-discardable, faster, reusable and responsive, than printing a static 3D object.

1. Advantage for the visually impaired 2. Artistic value 3. Absence of elements which bring about screen addiction 4. 3d representation without the need to use devices like a mouse or touch screen to rotate information on a 2d screen to get 3 d Information

More natural and real.

I think as mentioned above (sorry I hadn't read this question before answer the previous one). 3D displays help users visualise. I think it would be a prototype of a 3D printed prototype. The benefits of 3D printing are that you don't need to make moulds for your design or invest in any tooling costs. However 3D prints aren't changeable like lets say even moulding clay. Moulding clay on the other hand is challenging if you want it digital as you would need to scan it. 3D screens could bridge that gap. You can manipulate on the computer and see results immediately via a 3D display, reducing the time to print or the need to print various forms... Or if tangible displays advance even further, maybe manipulating an object can happen in this screen itself...

1. Flexible , unlike hard wired PC screen , so You can change the texture etc 2. Feedback - the user can receive tangible feedback from the screen as the screen configures itself 3 exciting - appeal to younger generations

The types of tangible displays can be dramatically diverse, so they can be tailored according to the purpose and the content.

Tangible displays could allow a more organic approach to 3D printing, e.g. manually 'sculpting' shapes in a similar way to working with clay. Also could be used for 'previews' of the final 3D printed object. Objects could be 'rendered' using tangible interface e.g. placing objects on the tangible interface to identify shape/weight.

I have mixed feelings about tangible displays. On the one hand, it again is good for reducing cognitive load. For ex think of trying to solve a rubiks cube on screen vs doing it on an actual 3d cube. However, on the other hand, (most) tangible displays are not good for showing flux of information - for ex a computer screen can go though a lot of information really fast because of its refresh rate. (Also see my next response) I think tangible displays need to find their niche.

Maybe be able to customise the UI we needed, and is is able to lower the boundary for making and designing technology products.

They would probably feel more natural, giving more haptic feedback than a screen

they seem more fun, cause in 3D printing the machine does the work and this is you doing it in a way. also if you make a mistake it seems easier to fix it with when using a TUI than 3D printing, cause in the latter case you see the mistake probably once you're done, and TUI's would probably be re-touchable.

You can see it, touch it, feel it, simply know the things in front of you rather than struggling with the simulation of 3D model on a 2D screen. It just follow the way that we understand thing when we were still a baby, which is quite nature. Especially for something with complicated structure, like DNA model or car engine, a tangible model would be much easier to understand.

The use of the 3rd dimension outside of a screen. It's sometimes hard to perceptualize 3d information on flat 2d displays. The addition of the 3rd dimension might allow for unique ways for visualizing info

if you are referring to tangible displays like 3D printers, it would be definitely great advantage to copy and build house, food, car, and duplicate them quite easily so cost effective, and efficient time wise, resource wise.

Question 3: There are some prototypes in large labs which showcases dynamic tangible user interfaces, which showcases different shapes or information as rapidly as you see on your screens today. What context do you think would this be useful?

Anything where one benefits significantly from the visualisation of 3D content. Lets take text as an example. There is no significant benefit of displaying text using a tangible display as your eyes recognise the words and interpret the meaning of them. 3D is not required. Then you have optical illusions like the vase / 2 faces images. Those make use of our brain needing more information: if there was depth then everybody would see either a vase or 2 faces but not both depending on what you focus on. One may therefore conclude that things which don't have any symbolic representation and requires a need for the extra depth in order for its reader to understand it can significantly benefit. I would say designers are one such audience.

For real estate agency when they show prototypes to engineers or customers.

1.Tangible displays will find great use as a dynamic realtime 3d land mapper for off road vehicles,especially where the driver prefers to be hands free and to not use his fingers to rotate a 2d image on a screen in order to get a 3d awareness of his surroundings 2. As visual elements in the creative arts..especially as props on stage for music shows,dynamically reacting to the music 3 . 3d land mapper for low flying helicopters,or for submerged vehicles which have to navigate the bottom of water bodies 4.Dynamic mould for modelling. All parts of a full product can be moulded by one tangible element with dynamically changing moulds. No need for an assembly line concept. 5. Topography mapping

For education needed in remote area. Young kids be able to access information through touching. Or for blind...as i mentioned before.

Any context related to work an collaboration where real time feedback can support flow and collaboration

as i mentioned in first question, it will be useful to have those kinds of things where it's not easy for human to access so that we can control and manage them from the distance. maybe under the oceans or even moon, etc

again probably architecture, maybe even security, like if you have a team that needs to secure a place, it'd be useful to be able to quickly go through 3D representations of its parts to get a better understanding rather than having to use 2D and then make it 3D in your head.

Architecture allowing people to see how an environment could grow and change or allowing you to see the movement of people around a site Fashion industry applications - showing how different clothing designs might fit different body shapes Interior design - helping people see how they could change the inside of their house eg knock down walls , change colour, add loft Medicine - help people picture the inside of their body eg help them visualise white blood cells attacking a virus and thus helping them recover quicker from cancer

This depends on the kind of tangible display and the kind of information. A sculpting tutorial application would definitely benefit, because the focus is mostly on the 3D aspects of one object. But, say, taking a wild example, if a tangible display were creating puppets to represent a movie, it can become confusing with a lot of moving objects.

Visualisation of rapid and dynamically changing information

Very useful.

Game advertisement or something that help people to improve relationship, like break ice between strangers or increase interaction between friends...

Collaborative work. Multi-user. Multi-location. Visualise data in 3D.

It can be applied in like museums as a substitute of the dry introduction labels, so that people may be more engaged in learning something about the exhibition.

When watching the MIT video, I thought of educational applications even before they showed it âĂŞ I can imagine the benefit to children being able to demonstrate to themselves how a graph / some geometric object changes when quickly changing some variable. This might be even cooler with a highly responsive tanglible display. Communicating with friends over long distance comes to mind too (even though it would be really dorky), or anything where the interface would be able to mimic my own movements quickly. I wonder if this has applications for surgeons?

Question 4: In the future it might be possible to create tangible interfaces of in the scale of nanometers, or as large as cities. What could be the potential uses of this type of tangible interfaces in scale?

For large scale displays/interfaces as large as cities where you're talking about not just displays at that scale but changing environments. This could allow cities to become more dynamic to meet the needs of its citizens in a faster fashion. Nanometers...not sure

ah..for large one.. magical wonderland?

Advertising or surgery.

Thinking in large stuffs, if you can build a city or some buildings that changes its structure based on the weather and conditions would be awesome.

1. Urban warfare simulations can have multiple scenarios or even dynamically changing landscape leading to a higher training level for the police/military if the scale is large. 2. Nano stamps with dynamically alterable seals.

Prototype/visualise at human scale e.g. city, street, building, furniture, micro-architecture, engineering. Dynamic spaces, e.g. events, security, Allow different degrees of '3D resolution'. Manufacturing. Transport.

again maybe building houses, city, etc in the universe like the moon, etc or even under the water

A portable case that can be expanded to as large as a car but can be folded just as small as a case as well. So it saves the parking space.

nanometres - maybe like implants that can change their shape, like if something has to be lodged in your body to release drugs, adn it could be a pill you swallow which then 'grows' once it's got to where it needs to be or something like that. large - theme parks, like they could change the features of buildings and other things, decorative of course, so that it saves money. maybe even stuff on real buildings for living in that can re-new their style, art installations i suppose too

Dynamically changing signages and markings on roads

When thinking of tiny ones, I again think of medicine. Perhaps there is something you could insert into the body that responds by changing its shape and size to small-scale changes inside our bodies. This is obviously a silly example, but for my lack of any sort of medical knowledge, I am imagining for example an object inside a tube/capillar/vein what have you, that has the responsibility of blocking the "tunnel" in certain situations. A shape changing trinket seems right for the job! Or how about indicators on your skin that are easy to feel with your fingertips, that tell you anything from vitamin deficiency to medication reminders. I can't really imagine anything in the scale of a city.. Who would be the user? Nobody could perceive the whole thing. Hmm, perhaps injury prevention? Responsive asphalt âĂŞ if somebody is in an accident and thrown from their car, it would amortize instantly and absorb the shock by gradually decelerating or cushioning their fall or something.

You could lets say measure things super accurately i.e. orthopaedic shoes (I am thinking about toy with the pins and you put your hand through it). Or your could 'try on' things. 3D prints have made it possible to have custom-made casts for broken arms, prostheses etc. However you have to commit to a shape or design before trying it on. This allows you to explore the shape even before the 3D print.

Think about electricity. In todays world, most requirements of mechanical energy can be met by having an interface to use electricity; electricity is something like the stem cell of energy. Tangible interfaces at scale can serve as a similar solution - all constructions, big or small, would have this as the basic substance. Of course, at some point of time we need to figure out how to bestow "properties" to such interfaces - because real things are not just about how they look, but what properties they have so they serve the purposes they serve.

1. Small ones good for medicine eg treating an internal organ 2. Large ones good for leisure industry eg adventure game where you explore constantly changing landscape - climb up it, slide down 3.trainjng for Fire fighting or car crash scenes - reconfigure environments quickly to let firemen practice different rescues

I have never think about this. But if you make it smaller it would be able to embed in living beings.... which will be useful for biology, medical used..i think. For the bigger one I don't really know HAHA! For kids to play or for arts maybe. Or for transportation?

Question 5: Any wild ideas? I would like to hear your wildest concepts of potential application of this technology?

Can you change the shape of cars whenever you want?, or change the aerodynamic of airplanes to make more efficient and less turbulent a flight?

Reduction of material usage/wastage. Let me digress. Think about virtual reality. When you have those googles on and you look to your right, does the environment in front of you, to your left or behind you, need to exist? No. When I drive back home from office, step out of my car and go to my house, do I need my car? No. Can the car morph into that part of reality that I am actually going to interact with now? You did say wild :)

Tangible roads? Like while people are walking on the road, the road will show something surprising, it's especially interesting when it comes to celebrating something.

Tangible music

I think my ideAs have been wild already but ... Maybe use it for training scuba divers underwater Take it to the Moon where gravity gets in the way of normal pointing and clicking Put it into orbit or Take it to Mars and it could adapt to whatever atmosphere

magnetic levitation display... can form anything individually in a space so we can interact, touch, grab, pinch... etc. would be wonderful if I can have a real galaxy suspend in my room during the night... and in the morning it forms a small sun to wake me up perhaps?

i think i must repeat the same answer as the above

If we were able to get a 3D scan during surgery, a very high resolution 2.5 shape display might be able to create a magnified representation of the patient and the area being operatied. This could be useful in laser and laparoscopic surgery

1. Body suit/Visual alteration..a cloth covered with tangible elements can effectively alter the look of a person by adapting to preprogrammed settings at the touch of a smartphone screen . This would work with altering the muscular appearance of a person,while advanced versions would change facial appearance(at the nano scale) 2. The body suit could also make use of each individual element to reduce impact dynamically. The intelligent suit would sense the proximity of a surface and increase the impact absorption capability of the area about to receive the impact. 3. Dynamic visual alteration for vehicles,buildings...well...ANYTHING. 4.

Remove bombs or something dangerous for people to do, asking for absolute precision as well.

Online shopping. Lets say you have one of your new tangible displays with a retina-display resolution. You are on the Tiffany jewellery website and looking at necklaces. If you are going to be spending tens of thousands of pounds on a necklace or piece of jewellery wouldn't you want to see it 3-dimensionally before you buy it or even touch something resembling it? That would be pretty amazing.

I am not a creative person so let me sent you to creative ones: anything in Star Trek, 2001: A Space Odyssey...or the robot in interstellar.

Dynamic habitats for wild animals? Is that wild? I'm thinking of some sort of robotic control interface where you can take advantage of the 3d plane to support the control of robots/drones/groups of drones but still have the benefits of a 2d control system

i kinda think my previous ones were pretty wild. i tried to come up with something else for a minute or two but nothing comes to mind.

I think I'm not coming up with anything better than responsive tangible asphalt.

9.8 Piccolo Code

```
/**
* This code is to perform a pickup and drop of display elements of a shape display
* using gcode and nodejs
* Author : Sandeep Zechariah George Kollannur
**/
#include <Servo.h> //Needed in Piccolo Lib
#include <PiccoloLib.h> //include the Piccolo Lib
PiccoloLib piccolo; //Make a instance of the Piccolo library for control

float maxR = piccolo.X.getBedSize(); //reach to end of Piccolo draw area.
float minR = 1; //Min spiral radius.
float maxPickUpHeight=0;
float pickUpHeight =14;
float ZFloatHeight = -20;

void pickPin(float x, float y,float height= maxPickUpHeight);

void setup()
{
    piccolo.setup(); //Setup Piccolo
    piccolo.home(); //Tell Piccolo to goto it's home position.
    pinMode(12, OUTPUT);
    digitalWrite(12, LOW);
}
void pickPin(float x, float y,float height)
{
    piccolo.move(x,y);
    delay(1000);
    piccolo.moveZ(pickUpHeight);
    switchMagnet(1);
    delay(1000);
    piccolo.moveZ(height);
    piccolo.moveZ(ZFloatHeight);
    delay(1000);
    switchMagnet(0);
    //delay(500);
}
void switchMagnet(int sw)
{
    if(sw==0)
    digitalWrite(12, LOW);
    else
    digitalWrite(12, HIGH);
}
void loop(){
    pickPin(10 ,10,10);
    delay(5000);
    pickPin(208 ,208,10);
    delay(5000);
}
```

Listing 1: Arduino based code for basic actuation of the shape display

This code is available online at `https://github.com/sandeepzgk/ShapeDisplay`.

9.9 Server Code

```
/**
 * This code is to create an abstraction layer and to create high level functions
 * for actuation using a numerical control for actuation of shape display input
 * received via HTTP protocol using gcode and nodejs
 * Author : Sandeep Zechariah George Kollannur
 **/
var SP = require("serialport").SerialPort;
var serialPort = new SP("COM3",
{
  baudrate: 115200
}); //COM3 is used because my computer(WIN) connects to COM3 for this device, might differ for different devices

var isOpen = false;
var isInitialized = false;
var isMounted = false;
var xMax = 108;
var yMax = 125;
var zMax = 78;
var xMin = yMin = zMin = 0;
var xBase = 44;
var zBase = 76;
var xFactor = 3.125;
var zFactor = 3.6;
var heightFactor = 0.32;
var yFloatHeight = 12;

serialPort.on("open", function()
{
  console.log('connection opened');
  isOpen = true;
  serialPort.on('data', function(data)
  {
    var datastr = '' + data; //the '' is used to make the data show strings otherwise it will show buffered ascii
    console.log(datastr);
    if (datastr.indexOf("echo:Hardcoded") > -1) //"echo:Hardcoded" is a string that is sent towards the end of initialisation
    {
      console.log("Device Initialized")
      setSpeed(1);
      preInitActivities();
    }
  });
});

function preInitActivities()
{
  console.log("PREINITACTIVITIES")
  goHome();
  isInitialized = true;
}

function sendData(command)
{
  if (isOpen)
```

```
  {
    console.log("COMMAND SEND::" + command)
    serialPort.write(command + "\r", function(err, results) //"\r is important for the commands to be recognized"
      {
        console.log('err ' + err);
        console.log('results ' + results);
      });
  }
}

function goHome()
{
  sendData("G28"); //gcode Data to go home
}

function moveX(location)
{
  if (location >= xMin && location <= xMax) //not to exceed the limits of the machine
    sendData("G0 X" + location);
}

function moveY(location)
{
  console.log("YLOCATION:" + location + "YMIN:" + yMin + "YMAX:" + yMax)
  if (location >= yMin && location <= yMax) //not to exceed the limits of the machine
    sendData("G0 Y" + location);
}

function moveZ(location)
{
  if (location >= zMin && location <= zMax) //not to exceed the limits of the machine
    sendData("G0 Z" + location);
}

function moveXY(x, y)
{
  if (x >= xMin && x <= xMax && y >= yMin && y <= yMax) //not to exceed the limits of the machine
    sendData("G0 X" + x + " Y" + y);
}

function setSpeed(speedFactor) // speedFactor is the speed from 1x to 10x
{
  sendData("M220 S" + speedFactor * 100); //this speed is conveyed as percentage values to gcode
}

//this function gets the mount plate for towards the mount position and getRead for mount.
var waitforMount = setInterval(function()
{

  if (isInitialized && !isMounted)
  {
```

```
    moveY(yMax);
    clearInterval(waitforMount);
    isMounted = true;
  }

}, 1000);


//x,y - in range 1 - 20 and height in range 1 - 40, and has to be a whole number
function pushPin(x, y, height)
{

  if (x > 20 || y > 20 || height > 40)
    return;
  //These floor functions are used for sanity checks.
  x = Math.floor(x);
  y = Math.floor(y);
  height = Math.floor(height);
  moveX(xBase + x * xFactor);
  moveZ(y * zFactor);
  moveY(yFloatHeight - heightFactor * height)
  moveY(yFloatHeight);
}

var app = require('express')();
var express = require('express');
var server = require('http').createServer(app);
app.use(express.static(__dirname + '/'));
var io = require('socket.io')(server);

server.listen(3000);

io.on('connection', function(socket)
{
  socket.on('ev', function(data)
  {

    switch (data.command)
    {
      case 'load':
        moveY(yMax);;
        break;
      case 'pushPin': //console.log("X:"+data.x+"Y:"+data.y+"H:"+data.height);
        pushPin(data.x, data.y, data.height);
        break;
    }
    console.log(data.command);
  });
});
```
Listing 2: NodeJS based server code for bridging the user-interface with the Numerical control using *gcode*

This code is available online at `https://github.com/sandeepzgk/ShapeDisplay`.

9.10 User Interface: Client Side Code

```
/**
 * This code is to create the user interface (UI), and to send high level
 * instructions to the server code for rendering
 * Author : Sandeep Zechariah George Kollannur
 **/
var socket = io('http://localhost:3000');
socket.on('news', function(data)
{
  console.log(data);
});


function loadPosition()
{
  socket.emit('ev',
  {
    command: 'load'
  });
}

function pushPin(x, y, height)
{
  socket.emit('ev',
  {
    command: 'pushPin',
    x: x,
    y: y,
    height: height
  });
}

var heightArray = [];

function processImage()
{
  var c = document.getElementById("myCanvas");
  var ctx = c.getContext("2d");
  var img = document.getElementById("myImg");
  ctx.drawImage(img, 0, 0);
  var imgData = ctx.getImageData(0, 0, c.width, c.height);
  // invert colors
  for (var i = 0; i < imgData.data.length; i += 4)
  {
    var r = imgData.data[i];
    var g = imgData.data[i + 1];
    var b = imgData.data[i + 2];
    var a = imgData.data[i + 2];

    var grey = (r + g + b) / 3;
    var currentHeight = Math.floor(grey / 8); //to get a nice range from 0 - 31 for
         our display
    heightArray.push(currentHeight);
  }
  ctx.putImageData(imgData, 0, 0);
}

```

```

var x = y = 1;
var counter = 0;
var string = "";

function sendImageData()
{

  var myInterval = setInterval(function()
  {
    var h = heightArray[counter];
    counter = counter + 1;


    console.log(h);
    pushPin(x, y, h);
    x = x + 1;
    if (x == 21)
    {
      x = 1;
      y = y + 1;
    }
    if (y == 21)
      clearInterval(myInterval); //end of the loop

  }, 1000);

}
```
Listing 3: Client Side Javascript

This code is available online at https://github.com/sandeepzgk/ShapeDisplay.