Digital Foam: A 3D Input Device

Research Thesis for the Degree of Doctor of Philosophy

Ross Travers Smith

Principal Supervisor: **Wayne Piekarski**
Associate Supervisor: **Bruce Hunter Thomas**

University of South Australia

Wearable Computer Laboratory
School of Computer and Information Science
Division of Information Technology, Engineering
and the Environment
University of South Australia

Abstract

This dissertation investigates deformable computer input device technologies to facilitate capturing complex physical-world gestures. By capturing the physical gestures and using appropriate haptics, it is possible to create virtual models using pinching and squeezing gestures similar to those used when sculpting clay. To date, most desktop modelling applications employ pointing devices that capture a single cursor location to manipulate a model with tedious sequential steps. One reason for this is developers have focused efforts on adopting applications to work with generic two-dimensional pointing devices, such as a mouse or digitising tablet. This is due to the difficulty of developing three-dimensional input technologies. In particular, deformable sensors capable of capturing natural sculpting techniques are undeveloped.

This dissertation presents a soft material sculpting metaphor, identifies free-form hand shaping techniques and explores deformable input device technologies to capture multiple-finger sculpting gestures with appropriate haptic responses. After exploring existing technologies, the need for a new sensing mechanism was identified that lead to the development of Digital Foam, a deformable input device sensor that captures its own geometry. The first prototype presented employs a flat deformable surface that demonstrates capturing multiple finger gestures simultaneously. To further leverage sculpting affordances, a second prototype employs a spherical design to optimise the spatial mappings between physical gestures and the virtual models. The purpose of this is to capture existing sculpting skills and provide an intuitive understanding of the operation. For example, when the user deforms the back of the device, this will deform the back of the virtual model. Both technologies are constructed of polyurethane foam and provide a pleasing haptic sensation that is analogous to shaping soft materials like modelling clay.

To explore the functionality of Digital Foam, a library of interaction techniques have been developed that support multiple-finger manipulation operations. The algorithms presented further support the spatial mapping between existing virtual models and the spherically-shaped Digital Foam device. To maximise the obtainable resolution of the sensor, an interpolation algorithm was also developed. To determine the accuracy and reliability of the sensor, a computer controlled apparatus was constructed, allowing a real-time comparison between the physical location of the mechanical finger and the touch-point measured on the Digital Foam surface. The results showed a performance improvement using the interpolated location compared to the raw sensor data alone. The development of Digital Foam has allowed the exploration of deformable materials for input device technologies and investigates a novel human computer interaction methodology that shows promising results.

Declaration

I declare that:

- this thesis presents work carried out by myself and does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university;
- to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text; and all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.

Ross Travers Smith
Adelaide, September 2009

Wayne Piekarski
Adelaide, September 2009

Bruce Hunter Thomas
Adelaide, September 2009

Contents

List of Figures

List of Tables

Inspiration

At the beginning of my university studies I was intrigued by a student wearing a Head Mounted Display slowly pacing up and down the university quadrangle. He appeared oblivious to people staring at all the wires and electronics strapped to his body, showing enormous concentration to what appeared to be invisible objects no one else could see. He made precise movements and appeared to be picking, pinching, moving and placing things all around his body. I soon realised his fingers were electrically connected to a computer system that recognised his movements, and using this special computer system he could interact with a world I could not see. I was very curious to find out what and how he was able to be so immersed in his own fantasy land. Having observed what I considered at the time an "unusual cyborg looking student", my interest in new computing input devices and 3D environments was born.

Acknowledgments

Writing a thesis has been both an enjoyable and challenging task, there are many people I would like to thank for their support, encouragement and guidance they provided during my studies.

Supervisors are a critical aspect to completing a PhD degree successfully and I have been lucky enough to be guided by two of the best, Doctor Wayne Piekarski and Professor Bruce Hunter Thomas. You have both guided me through a very long journey in which your valuable insights and contributions have made it a successful one. Thank you both very much.

The Wearable Computer Laboratory is a unique and inspiring place to have studied and worked in for the last 8 years. Since my first summer internship in 2001where I was warmly welcomed and immediately felt part of the team. Many people have joined and left the wearable lab over the years and I have been lucky enough to study and work alongside them on many interesting projects. A special thanks to Ben Close, Ben Avery, Aaron Toney, Peter Hutterer, Aaron Stafford, Rebecca Witt, Wynand Marais, Michael Marner, Robert Kong, Andrew Cunningham and all the others members of the team.

Co-Workers and those I have studied alongside at the University of South Australia have also supported me in a variety of different ways and I would like to thank you all. Katie and Tanya who have helped me with conference travel and much more. David Kearney who provided quick and useful insight into the ways of PhD studies. Pippa Avery and Dennis Hooijmaijers who I studied alongside at various times. Stewart Von Itzstein and Grant Wigley for going on lunch runs and providing lots of advice towards my studies and research.

Reviewers take on the task of reading a thesis and providing a critical assessment, this is no quick or easy task. I would like to thank Professor Masahiko Inami and Morten Fjeld for reading and assessing my thesis. You have both provided valuable contributions that have been incorporated into the final version of my dissertation.

Friends and family have kept me sane by keeping me in touch with the enjoyable and important things in life. Thanks to the bowling crew Garry Reiner, Sue Roberts, Keith Smith, Christina Colt, Zac Krebbekx and all the league teams. Special thanks to Sunee Holland for her support and friendship over the years. Finally, I would like to thank all my family, I was blessed to be given such a motivated, inspiring, supportive and understanding family. Thank you for everything Mum, Dad, Keith, Andrea, Gregory and Genevieve.

Author Publications

R. T. Smith, B. H. Thomas, and W. Piekarski. Digital Foam Patent US. Application Number: 12/381147, 2009.

R. T. Smith, B. H. Thomas, and W. Piekarski. Tech Note: Digital Foam. In IEEE Symposium on 3D User Interfaces, pages 35-38, Reno, NV, 2008.

R. T. Smith, B. H. Thomas, and W. Piekarski. Digital Foam Interaction Techniques for 3D Modeling. In VRST 08: Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology, pages 61-68, Bordeaux, France, 2008.

R. T. Smith, B. Avery, and B. H. Thomas. Lightweight Hand and Arm Tracking for Mobile Augmented Reality. In ISWC: Proceedings of the Twelfth International Symposium on Wearable Computers, pages 105-106, Pittsburgh, PA, 2008.

R. T. Smith and W. Piekarski. Public and Private Workspaces on Tabletop Displays. In AUIC 08: Proceedings of the Ninth Conference on Australasian User Interface, pages 51-54, Wollongong, NSW, Australia, 2008.

R. T. Smith, W. Piekarski, and G. Wigley. Hand tracking for Low Powered Mobile AR User Interfaces. In AUIC 05: Proceedings of the Sixth Australasian Conference on User Interface, pages 7-16, Newcastle, NSW, Australia, 2005.

W. Piekarski and R. Smith. Robust Gloves for 3D Interaction in Mobile Outdoor AR Environments. In International Symposium on Mixed and Augmented Reality, pages 251-252, Santa Barbara, CA, 2006.

B. Avery, R. T. Smith, W. Piekarski, and B. H. Thomas. Designing Outdoor Mixed Reality Hardware Systems. In Engineering of Mixed Reality Systems. Springer book chapter. 2009

W. Piekarski, R. Smith, and B. H. Thomas. Designing Backpacks for High Fidelity Mobile Outdoor Augmented Reality. In ISMAR 04: Proceedings of the Third IEEE/ACM International Symposium on Mixed and Augmented Reality, pages 280-281, Arlington, VA, 2004.

W. Piekarski, R. Smith, G. Wigley, B. Thomas, and D. Kearney. Mobile Hand Tracking Using FPGAs for Low Powered Augmented Reality. In ISWC 04: Proceedings of the Eighth International Symposium on Wearable Computers, pages 190-191, Washington, DC, 2004.

N. Cooper, A. Keatley, M. Dahlquist, S. Mann, H. Slay, J. Zucco, R. Smith, and B. H. Thomas. Augmented Reality Chinese Checkers. In ACE 04: Proceedings of the 2004 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology, pages 117-126, Singapore, 2004.

1

Introduction

This dissertation presents my contributions to the development of new 3D input devices and supporting interaction techniques for use in virtual, augmented and personal computer environments. Computer input devices allow computer systems to capture physical world data using electrical and mechanical sensors. Electrical signals generated by sensors are sent to a computer system enabling the physical world information to be captured. Input devices both facilitate and direct the design of human-computer interactions (HCI). Most desktop PCs are equipped with the well known keyboard and mouse input devices. The computer keyboard is an adapted version of the mechanical typewriter designed in the 1700s to support dictations, transpositions and compose documents. Each key is mapped to a symbol allowing users to create typed documents by physically depressing the keys. A large achievement of the mechanical typewriter is that type speeds exceed that of what is can be achieved using a pen and paper [BROW88]. The computer keyboard is an excellent example of the benefits that can be achieved using an input device designed for a specific task.

In 1968 Douglas Engelbart and co-workers publicly presented their invention the "X-Y Position Indicator for a Display System", commonly known as the mouse [ENGL67]. The computer mouse was designed specifically for use with a computer system, and was presented with interaction techniques using a 2D graphical mouse cursor. Interaction techniques using a mouse as an input device continue to develop today. Since its original design (shown in Figure 1.1) improvements in resolution, update rate and additional features have optimised and improved the design. In credit to Engelbart's vision, the design principle still uses a 2D sensor to capture the device movements and control a cursor location.

The development of three-dimensional input devices and techniques is immature in comparison to two-dimensional devices like the mouse [FROH00b]. Early computer systems quickly embraced paper based record keeping tasks that were previously either handwritten or mechanically typed onto paper. The two-dimensional nature of the paper record system was quickly adapted to the two-dimensional nature of computer environments. Although pioneers of three-dimensional systems, such as Sutherland [SUTH65], performed initial work at the same time as the development of the mouse, processing power for rendering 3D graphics, as well as 3D tracking technology, was even more limiting than in 2D. More recently, as computing power continues to increase and dedicated high performance graphics accelerators have become readily available to the public, there has been increased demand for the development of three-dimensional interaction techniques and input devices [HERN94]. The direction and design of new interaction techniques is highly dependant on the type of computer input device used to capture the physical world data [FROH00b]. A common desktop computing environment will use a two-dimensional input device, such as a mouse, to control a 3D environment. Various mapping techniques and widgets are employed that allow users to navigate and manipulate all axes of the 3D environment using a 2D mouse.

Tracking technologies that provide 3D position and/or orientation data, such as the Polhemus Fastrack[1] with 6 degrees of freedom (DOF) or the Intersense InertiaCube2[2] with 3 DOF (shown in Figure 2.4(b)), are commonly employed in three-dimensional virtual and augmented environments. For example, Polhemus electro-magnetic sensors attached to human

[1] http://www.polhemus.com/

[2] http://www.isense.com/

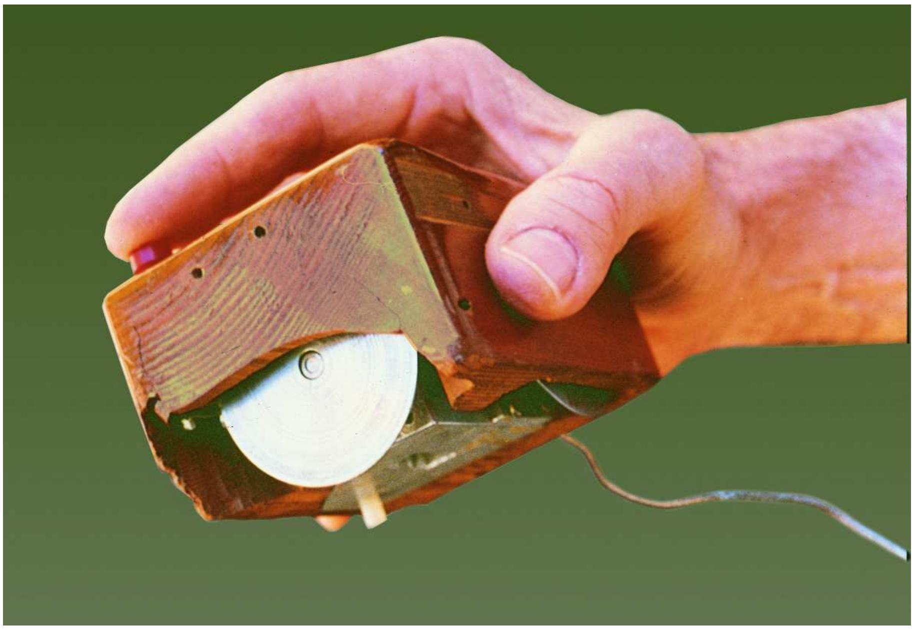


Figure 1.1: First mouse device developed by Douglas Engelbart and William English. (Reprinted with permission from SRI International)

limbs capture human movements allowing virtual recreations. More recent commercially available game consoles, such as the Nintendo Wii and Sony Playstation 3, have adopted these technologies and equipped their controllers (such as the Sony PS3 controller shown in Figure 1.2(b)) with accelerometers allowing a range of gesture based interactions to be performed. The Cubic Mouse [FROH00a] and Tango [PAIX05] (shown in Figure 2.14 and Figure 2.17 respectively) are additional examples of hand-held input devices used to navigate and manipulate 3D data [FROH00a].

Figure 1.2: Three dimensional input devices: (a) Intersense Inertia Cube, a hybrid orientation sensor often used for tracking user head orientation. (b) Sony Playstation 3 controller equipped with inertial sensors. (c) Fakespace Cubic mouse, a three-dimensional input device capable of navigation and manipulation operations. (Reprinted with permission from Bernd Fröhlich, image taken by Jeremy Eccles). (d) Tango, a prototype capacitive input device designed to capture finger gestures of the human hand. (Reprinted with permission from Dinesh Pai - University of British Columbia)

Although new input devices and techniques are being developed to assist with 3D tasks, humans still find free space three-dimensional interactions difficult [HERN94]. On-going research is addressing the complexities of three-dimensional environments and directing future design guidelines [BOWM01, SEAR03, LEEX05]. A mouse, for example, does not support direct touch. To move the cursor on a display, the user moves their hand holding the mouse and observes the cursor move on the display. A mental mapping of the device location allows the user to understand that when they move their hand up, the cursor will move to the top of the screen accordingly. A touch screen is an example of a device that supports direct touch, for example, the cursor on the screen is moved by touching the display directly. Popularity of direct manipulation interfaces [SHNE86] is also increasing, the direct touch design removes the need for mental spatial mapping between the input and output device. However, direct touch is only currently supported by some hardware devices, and the occlusion of the user's fingers (i.e. when using a touch screen) is also a limiting part of the design.

In HCI, affordance describes the properties of an object and the action possibilities which are perceivable by the user [NORM88]. The direct touch interface used on a touch screen is an example of leveraging the user's existing understanding of the physical world to optimise the interface design. For example, touching a button on the screen is more intuitive and does not require the same training to navigate a cursor with a mouse. Another interesting area where affordances can be leveraged for interface design is in clay modelling. Clay and similar materials have been used for sculpting physical models for thousands of years. During my childhood, my parents made Play-doh® for me to play with. At a very young age I became familiar with the feel of Play-doh® and started to learn some simple sculpting techniques. This familiar understanding of basic sculpting techniques has lead me to investigate how a similar input device can be constructed for a computer. This dissertation investigates how both the affordance of clay sculpting techniques and a three-dimensional direct touch interface can be used for the design of new computer input devices. The goal is to leverage a user's existing modelling skills and their understanding of physical world materials to optimise the design.

The goal of this dissertation is to develop a new computer input device that will allow users to sculpt 3D computer models using similar techniques employed when sculpting Play-doh®, clay, plasticine and other malleable materials. The input device will be physically constructed to resemble these materials so that the interaction techniques developed can leverage a user's existing familiarity and understanding of these processes to assist in 3D modelling operations. Figure 1.3 depicts an artistic impression of a user sculpting a three-dimensional model using a sphere shaped prop that captures the user's finger gestures using a deformable input device and a sculpted virtual model on a display. I intend to investigate the development and design of new input devices that capture natural human gestures and movements when performing specific tasks such as sculpting.

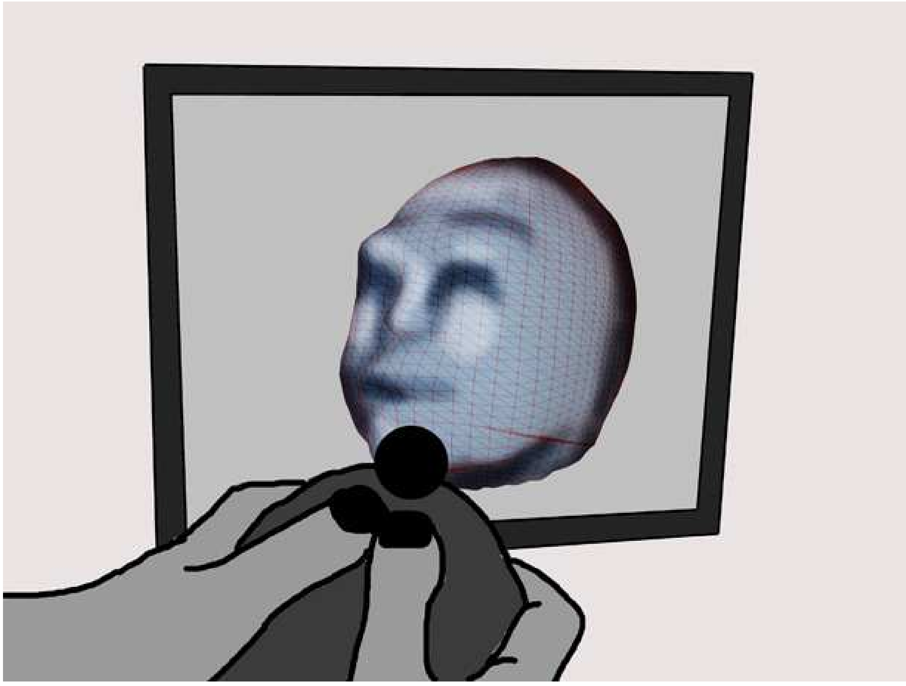


Figure 1.3: Artistic impression of user sculpting a 3D model using the proposed input device

1.1 Problem statement

The windows, icons, menus and pointers (WIMP) paradigm pioneered by Xerox Star [JOHN89] has been refined over many years and leverages the use of two-dimensional devices. The development of three-dimensional computer input devices is an area of research that has not developed at the same rate and is immature in comparison [FROH00b]. Humans also find it difficult to understand and manipulate computer generated 3D data, because some cues that enable understanding of the environment are missing [HERN94]. The question is raised as to what devices and techniques can be created to help overcome these limitations in 3D.

Currently, using pointing devices to create 3D models does not provide the same freedom available in the physical world. Humans perform many tasks that use both hands and multiple fingers, allowing complex interactions. An engineer does not use one hand to build a bridge nor does a child use one finger to build a sand castle. Complex gripping and pinching gestures allow us to perform tasks with great expression and freedom. Using commonly available input devices within three-dimensional graphical environments, many interface techniques have been designed around the input devices and their limitations. To achieve this, a mapping between the device co-ordinates and task is performed rather than capturing the natural movements we use to interact with the physical world. This is often an undesirable outcome because the application functionality is reduced and it leads towards difficult to use interfaces that are not engaging like the real-world counterpart [FROH00b] [JUXX03].

Although devices such as pinch gloves or complex finger trackers offer alternative input means to capture complex finger movements, they have a number of limitations. Gloves must be donned, requiring increased setup time in comparison to other devices such as a mouse. Additionally, the gloves restrict finger movement and put a layer of material between the skin and the physical object, which reduces the tactile sensory perception that provides feedback when performing tasks that require touch. There is still a great deal of research required to explore modelling techniques employed within desktop, virtual and augmented environments. This dissertation argues that the functionality of the input device determines the techniques possible, and that a task specific device can be created to capture natural sculpting gestures that support functionality not possible using other existing devices.

1.1.1 Research questions

A number of interesting research questions are addressed in this dissertation that focus on the development of three-dimensional input devices and techniques. The following is a summary of the questions addressed:

- How can clay-like sculpting operations be performed in the physical world and captured on a computer system?
- What interaction techniques can be applied, allowing a range of sculpting operations to be performed?
- How can the proposed input device be used as a sole input device (i.e. without assistance of a keyboard, mouse, wand or pinch gloves)?

1.1.2 Research goals

The goal of this research is to answer the above research questions relating to the creation of new three-dimensional input devices and techniques. A summary of the specific goals are as follows:

- Develop new input devices that will allow the capture of finger-based sculpting operations.
- Develop new interaction techniques that will exploit the input device. Ideally, techniques are desired that capture basic sculpting-like operations to create new and modify existing 3D models.
- Evaluate the physical performance of the new devices created for this research, to verify they are robust and reliable enough for typical usage scenarios.

1.2 Thesis statement

Performing interactions in 3D environments using traditional 2D input devices increases the user's cognitive load, making human-computer interactions tiring and counter intuitive. Three-dimensional input devices provide a means of decreasing the user's cognitive load by providing direct spatial mappings between a user's physical world movements and the virtual environment [ZHAI96]. Employing direct manipulation techniques supports good user interface design affordances, providing a user with an intuitive understanding of how to use a system just by the way it looks [SHNE86, NORM88, NORM07].

Leveraging three-dimensional pointing devices to overcome the spatial mapping problems only addresses some of the shortcomings of existing computer input devices. The human cortex controls the sensory and motor systems, and dedicates a larger percentage of its power to the fingers in comparison to other limbs [ZHAI96, SAGE71]. The sensitivity and dexterity of our fingers is used in everyday physical world tasks, yet computer input devices have not fully exploited these acute sensory systems.

By capturing the complex gestures made by human fingers, a whole new range of human-computer interactions can be developed. Counter-intuitive and time-consuming modelling techniques such as sculpting and free-form modelling can be improved by more closely emulating physical world tasks. Taking advantage of our familiarity of the way the physical world works and building virtual environments to use the same interaction techniques, more intuitive human-computer interactions can be developed.

1.3 Research contributions

This dissertation presents a number of research contributions in input devices and human-computer interaction. The contributions are presented in order of technologies invented, interaction techniques developed and evaluation procedures performed:

1.3.1 Technologies

- **Digital Foam technology:** The conceptual idea of using an array of conductive foam sensors for use as an input device for a computing system. This new technology allows the real-time capture of the shape and geometry of a input device constructed from a piece of foam. The new sensor design has facilitated the design and construction of the novel input devices Flat Digital Foam and Spherical Digital Foam [SMIT08b, SMIT08d, SMIT09].

- **Flat Digital Foam:** Is the first prototype developed that demonstrates the use of a Digital Foam sensor array to capture a planar surface. Two prototypes have been designed and constructed, the latter more advanced one was constructed with a similar appearance to a digital tablet (e.g. Wacom[3]) with the addition of pressure capture and multi-touch capabilities [SMIT08b]. A number of new interaction techniques have been made possible using these new technologies, including 3D data capture, creation, manipulation and navigation.

- **Spherical Digital Foam:** A hand-held Digital Foam prototype designed to follow the clay sculpting metaphor. Two separate prototypes that follow the same design have been constructed. This iterative approach has allowed the construction techniques to be improved, and subsequently the resolution of the new technology to be increased [SMIT08d]. The prototypes allow the development of additional 3D sculpting techniques to be developed and tested.

1.3.2 Interaction techniques

- **Flat Digital Foam techniques:** A 3D cursor tracking algorithm was developed for a Digital Foam surface. The tracking algorithm calculates a 3D location with a greater accuracy than the physical spacing of each foam sensor. This is achieved by leveraging the physical properties of the foam surface by combining the surrounding sensor readings of any single touch point to find an interpolated cursor position. This algorithm is also extended to support multiple-cursor tracking simultaneously while maintaining a unique identification number for each cursor. A notable unique feature of this system is that no additional sensors or electronics need to be attached to the user during operation. Additionally, an application that demonstrates the dynamic addition of cursors in real-time was developed.

- **Spherical Digital Foam techniques:** A number of modelling techniques have been developed that follow a clay sculpting metaphor. Firstly, a free-form sculpting that allows 3D modelling to be performed. This is assisted with the half-hemisphere operating techniques that provides intuitive user control when performing modelling operations. Additionally, a touch based camera navigation technique that allows a user to view a virtual model using an orbital camera with Digital Foam is presented. Finally a menu system has been designed, presented and implemented that allows Digital Foam to be used as a sole command entry input device [SMIT08d].

[3] http://www.wacom.com/

1.3.3 Evaluation

- **Performance evaluation:** An evaluation of the Flat Digital Foam sensor array was conducted. A custom designed apparatus was constructed that allows an exact stroke to be performed and repeated many times. The experiment provides real-time data of the repeated stroke operations in which a statistical analysis is provided. Additionally, this experiment demonstrates the effectiveness of the cursor tracking algorithm, has been used to provide an analysis of sensor accuracy and error ratios. Finally, this procedure tested the mechanical reliability of Digital Foam.

- **Pilot user study:** A pilot user study was conducted to gather qualitative user experience data. The purpose of this study was to gather user acceptance data to assist with the iterative design of Digital Foam. As the technical construction of the device develops, the data gathered will assist with future design and evaluation directions.

1.4 Structure

Following this introduction, in Chapter 2, a summary of related work is provided that discusses a range of computer input devices, human-computer interaction design philosophies and interaction techniques is summarised. Chapter 3 presents the physical sculpting metaphor and discusses the adoption of clay-like sculpting gestures and techniques for a computer modelling system. Chapter 4 begins by discussing the search for an appropriate input sensor to capture aspects of the sculpting metaphor. This chapter continues by presenting the development and theory of the Digital Foam sensor, a significant contribution of this thesis. Following this, Chapter 5 discusses the interaction techniques developed to capture sculpting-like operations using the Digital Foam input device. Chapter 6 presents the evaluation performed to measure the Digital Foam sensor performance and an initial pilot study to capture user acceptance data. Chapter 7 provides a conclusion and discusses the future directions and possibilities for novel three-dimensional computer input devices. Finally, six appendices provide additional material created during the research performed for this dissertation including; the Digital Foam patent, Digital Foam schematics, Mechanical finger configuration details, conductive foam technical information, trial study questionnaires and details describing digital materials included with this submission.

2

Background

This dissertation is concerned with the development of three-dimensional task-specific input devices modelled on physical world interactions. This chapter presents a synopsis of input devices and associated technologies that have been used to guide the development of solutions to the research goals identified in Chapter 1. A number of new technologies have been developed during my research and are included so comparisons can be made. This chapter begins by providing a definition of a computer input device and the terminologies commonly used to categorise and describe their properties. Following this, a history of significant computer input devices including keyboards, pointing devices, tracking systems, malleable surfaces and task-specific devices is presented. Subsequently, a discussion on the hardware sensors used to construct input devices is described. After these technologies have been explained, various identifying characteristics that support the understanding and design of future devices is presented. Penultimately, a number of modelling systems that present free-form and sculpting-like manipulation techniques are summarised. Finally, a discussion describing a variety of three-dimensional environments that employ these devices and interaction techniques is covered.

2.1 Input device terminologies and definitions

Computer input devices capture real world data, allowing a connection between the physical world and a computer system. Devices are used to either log data, for example measuring and recording the temperature, or they facilitate an interactive means of human-computer interaction. Sensor technologies used to construct input devices support a range of different dialogues between human and machine. Some device operate through physical touch, i.e.

a mouse or keyboard, while acoustic sensors capture speech, optical systems allow vision processing, and neural interfaces measure brain functions. Computer systems respond to these interactions using a visual display or audible sounds that are easily communicated to the human perceptual systems.

This dissertation is concerned with devices used to perform three-dimensional modelling tasks, of particular interest are the range of hand-held devices that require physical contact to capture physical-world hand and finger movements to express modelling gestures in simulated environments. The design of input devices is diverse and they have been adopted to support the tasks of many disciplines. To better understand the properties of the devices there are a number of terminologies used to describe the physical sensor operations. These allow the devices to be categorised and assist the design of future devices and interaction techniques. Some variation in terminology are used throughout the research literature - this dissertation adopts the terminologies and definitions as presented by Zhai [ZHAI95] and Fröhlich [FROH00b, FROH06] and employs their use forthwith.

Isotonic devices are displacement, free moving or unloaded devices with either zero or constant resistance. Many isotonic devices exists, a common example is the computer mouse (a Microsoft wheel mouse is shown in Figure 2.1(a)) that employs a 2 DOF isotonic sensor. The Logitech 3D mouse (shown in Figure 2.1(b) is an example of a 6 DOF isotonic device. Studies have shown that isotonic devices are well suited to position control tasks such as moving a mouse cursor [ZHAI93a, ZHAI93b, ZHAI97].

Isometric devices, sense force but do not perceptibly move. Figure 2.2(a) is an example of a small 2 DOF isometric joystick handle that does not perceivably move when force is applied. During operation it senses how hard and what direction a user is pushing it. The SpaceBall 3000™ (shown in Figure 2.2(b)) provides 6 DOF tracking using isometric sensors.

(a) (b)

Figure 2.1: Isotonic free moving device examples. (a) Microsoft isotonic wheel mouse with 2 DOF. (b) Logitech 3D mouse providing 6 DOF.

(a) (b)

Figure 2.2: Isometric device examples. (a) AccuPoint 2 DOF isometric joystick mounted near home keys on a Toshiba laptop keyboard. (b) SpaceBall 3000 ™ is a 6 DOF isometric input device.

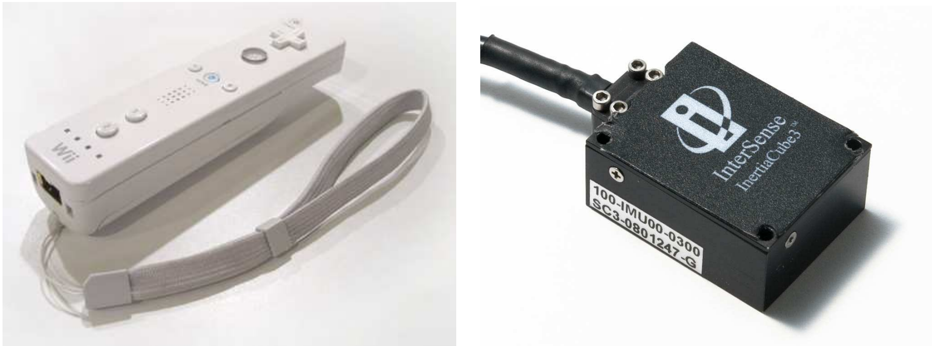
These devices are well suited to rate control tasks, for example, mapping the force or velocity of the sensor directly to the velocity of the cursor [ZHAI97].

Elastic Devices, are in-between isometric and isotonic devices, and provide a varying resistance. Specifically, they sense force increases with displacement. They are also referred to using the term spring loaded (Figure 2.3(a) provides an example of a suspended elastic grip device). The 3DConnexion SpaceNavigator™[1] (shown in Figure 2.3(b)) employs elastic sensors providing 6 DOF. These devices also often include a self-centring mechanism and like isometric devices are well suited to rate control tasks [ZHAI97].

[1] http://www.3dconnexion.com/

(a) (b)

Figure 2.3: Elastic device examples. (a) Elastic general-purpose grip device provides a visual description of an elastic operating mechanism [ZHAI93c, ZHAI95] (Reprinted with permission from Shumin Zhai - IBM Almaden Research Center). (b) The 3DConnexion SpaceNavigator™ 6 DOF elastic input device.



(a) (b)

Figure 2.4: Inertial device examples. (a) Nintendo WiiMote incorporates inertial accelerometers. (b) InertiaCube 3, a hybrid inertial device that includes accelerometers, gyroscopes and a magnetometer.

Inertial Devices, sense increased resistance with acceleration. Accelerometers measure acceleration forces along a single axis using nano-scale micro-electrical-mechanical systems (MEMS) [FOXL98a]. These devices suffer from accumulated drift over time, to overcome this limitation either the interaction techniques must accommodate the drift into their design, or inertial sensors are combined with a number of additional sensors to improve performance. The InterSense InertiaCube 3 (shown in Figure 2.4(b)) is a hybrid orientation tracker employing accelerometers, gyroscopes and a magnetometer that combines sensor measurements using a Kalman filter [HADD76] to overcome drift issues.

Viscous Devices, sense increased resistance with velocity of movement. A Phantom [MASS94] is a programmable haptic device that can emulate the feel of physical materials using mathematical models to express material properties. Fluids with different viscosities are easily emulated using a Phantom.

There are a number of emerging devices that blur the distinction between these categories. Hybrid devices incorporate the use of multiple sensor types, for example an isotonic (free moving) mouse with an isometric joystick installed in-between the mouse buttons. These devices are described using a combination of sensor definition and DOF discussions. Input device designers use these categorisations to assist with the design of future input devices and support the selection of appropriate sensor technologies for use with particular interaction techniques [ZHAI93c].

2.1.1 Tracked dimensions and input streams

Input devices track one or more dimensions, for example an audio mixing console uses sliders to control one-dimensional data. A computer mouse tracks two-dimensions to control the position of the cursor. Two orthogonally mounted sensors allow a single movement of a device to control two axes simultaneously, this is referred to as two-dimensional tracking. It is important understand that the coupling (or configuration) of the sensors changes the way users operate a device, and the difference between a device with two one-dimensional sensors and a device with one two-dimensional sensor. An “Etch-A-Sketch” ® (shown in Figure 2.5), in comparison to a two-dimensional mouse, provides a good example of a device with two one-dimensional sensors. Separate knobs move a stylus leaving a solid line on the screen, one knob controls the X position and the second knob controls the Y position [BUXT86, BUXT90].

As devices have developed, the use of multi-stream inputs has become a popular design. A wheel mouse provides an additional one-dimensional input stream operated with a single finger. The incorporation of multi-stream input mechanisms allows tasks such as document scrolling to be performed with one input while navigation of the cursor is performed using another input stream. Zhai suggests that the use of more advanced multi-input streams operated with both hands may support higher efficiency for both physical and cognitive loads [ZHAI04, LEGA98, BUXT90].

Figure 2.5: Etch-A-Sketch with separate control knobs for X and Y position control.

2.2 Input devices

With the popularity of the personal computer, there have been numerous prototype and commercially available input devices developed. Taxonomies describing input device characteristics have been described by Buxton [BUXT83] who presents a taxonomy based on device DOF, which is later extended by Mackinlay [MACK90] and Foley [FOLE84], and can be referenced for more detailed descriptions. This section begins by discussing common input devices, such as the keyboard and pointing devices to identify how they have been employed in both two and three-dimensional environments. This is followed by a detailed discussion of emerging devices that support whole-hand and multiple finger modelling, navigation and interaction techniques in three-dimensional environments.

2.2.1 Keyboards

Keyboards are a well established computer input device with a design layout adopted from the mechanical typewriter. Modern 104-key US English keyboards are constructed with an array of 104 one-dimensional buttons (or binary switches) marked with symbols to identify their functions. Used for their primary function, text entry, a practiced touch typist can type documents faster in comparison to handwritten documents [BROW88]. Both hands are regularly used while typing, for example when typing uppercase letters the little finger of one hand holds the shift key while the other hand's fingers push keys. Using combinations of keys such as shift and letters at the same time highlights that the number of possible key combinations is greater than the 104 keys available and that the keyboard is also a multi-touch device [BUXT07]. Used for text entry, the keyboard is a task-specific multi-touch bi-manual device that provides improved performance compared to handwriting English documents.

The keyboard is also used for tasks other than text entry such as navigation in first person shooter games, shortcut keys (or hotkeys) and mode-swapping functions within applications. First person perspective games use the keyboard to provide navigational functionality, for example W, A, S, and D keys control velocity based movements and mouse movements control the view direction allowing flying through a 3D environment. Modern computer aided design (CAD) environments, such as Autodesk's Maya®, 3ds Max® and Inventor®[2], support the creation of mathematical derived 3D models using a mouse and keyboard as the primary command and entry devices. Keyboards assist manipulation and navigation operations in three-dimensional environments using mode-swapping. For example, a 2 DOF mouse is mapped to perform a translation in the X and Y planes, this function may be altered by holding the control key, which swaps the translation axis to the X and Z planes.

[2] http://www.autodesk.com/

For its intended use the keyboard is a intuitive device, the symbols identifying the functionality of the buttons make its use self explanatory. However, when used in three-dimensional environments the binary buttons have been adopted to allow velocity control and abstract mode-swapping techniques. The problem with these techniques is they are not modelled on anything familiar in the physical world, so their operation is counter intuitive and increases the cognitive load for the user.

2.2.2 Pointing devices

The most common input device used on desktop computers today is the computer mouse [ZHAI04]. The first mouse prototype (shown in Figure 1.1) was presented in the paper "Display-Selection Techniques for Text Manipulation" by English and Engelbart in 1967 [ENGL67]. In the following year, Douglas Engelbart gave a public presentation demonstrating its use with networked computer tools. The wooden mouse prototype contains two orthogonally mounted wheels that rotate when slid along a flat surface (such as a table). Each wheel is attached to a potentiometer (linear resistive sensor) and used to measure the movement of the mouse.

Using the revolutionary mouse, Engelbart demonstrated a screen cursor selecting a block of text, copying it to memory and pasting it in a new location, a technique that to date is still used extensively. When working on documents to perform selection and text manipulation, only a minor spatial translation between the device and the output cursor is required. For example, when moving the mouse left and right on the table, the cursor moves left and right on the display, and when moving the mouse forward and backwards on the table the cursor moves up and down on the screen. These small spatial translations do not significantly increase the users cognitive load [SEAR03]. It is also common to use clutching, where the user picks the device up and repositions it. This allows a small physical working area to be used to manipulate a cursor endlessly along each axis [HINC94].

The mouse has also been adopted to perform interactions with 3D environments, one limitation of this is the mouse's sensor provides 2 DOF but to allow full control of a single point in a 3D space 6 DOF is required. To allow manipulations in 3D space using a 2 DOF sensor, either mode-switching or an additional input stream are required. For example, mode-swapping techniques, as previously described, use a separate input such as a keyboard to change the axis of operation. Modern mice often include an additional input stream such as a scroll wheel. The scroll wheel attached to many mice is a finger operated sensor that can be used simultaneously with the normal operation of the mouse. This multi-stream input provides 2 DOF + 1 DOF tracking and can be leveraged to allow more complex interactions or in this example mode-swap the operational axis [ZHAI99, HINC02].

Another consideration when using the mouse for three-dimensional interactions is the device provides a single tracked location and point of focus for user interactions, i.e. the cursor. This limits the type of interaction techniques supported by the device hardware and encourages developers to design techniques around the device's functionality [FROH00b]. Consider the scenario where a user's task is to bend two fingers on a virtual hand to an arbitrary new location (assuming simplified fingers are made up of one segment and rotate around only one axis). Using a mouse, at least two operations are required to reposition the fingers to a new location. Now consider using an alternative input device, if we track the tips of the user's fingers so the virtual fingers are controlled directly from the user's fingers with a one-to-one mapping. In this configuration, the user can move both fingers simultaneously to the new location. The purpose of these discussions is to identify that there are tasks that are not intuitive using a mouse, although this is not to say that the mouse does not have its place. Within two-dimensional desktop graphical interfaces it is likely to remain the pointing device of choice [SEAR03]. However, there are task-specific operations that are physically not possible to perform, such as the simultaneous movement of the fingers in the scenario

Figure 2.6: First mouse device developed by Douglas Engelbart and William English in 1967. (Reprinted with permission from SRI International)

presented, and is determined by the input device functionality.

There are a number of additional 2 DOF technologies that support pointing tasks providing similar functionality to a mouse. Pointing sticks (such as IBMs TrackPoint, Hewlett Packard's Point Stick, and Toshiba's AccuPoint) are a range of isometric joysticks that sense pressure to control the cursor direction and velocity. Isometric devices are well suited to rate control and velocity based movements, for example the pressure exerted is proportional to the speed of the cursor movement. Touchpads are commonly found on laptops and portable music players, they are relatively tracked isotonic devices that employ clutching [HINC94] and cursor acceleration techniques to extend the user's control of the cursor position. Touch screens are a transparent screen installed on a display. They provide a direct-touch absolute cursor control with a one-to-one mapping between the size of the display and the touch surface. Some touch screens and touchpad's provide multi-touch capability allowing multiple fingertips to be tracked simultaneously. Multi-point tracking allows finger gestures to be recognised, supporting interactions that are not possible using a mouse [HANX05, BAEC95]. For example, capturing pinch gestures to control the scale of an image. A limitation of touch screens and direct-touch devices is unlike other devices, during operation the user's fingers occlude parts of the display.

There are a number pointing devices with greater than 2 DOF. Graphical tablets, such as those by Wacom ®[3], use a proprietary electromagnetic resonance technology to track the location of the physical pen and incorporate a pressure sensitive tip. These devices combine an isotonic (free moving) sensor along the X and Y plane, and incorporate an isometric pressure sensor in the tip of the pen, that can be controlled simultaneously. The merged composition of the sensors provides a fixed working volume with 3 DOF. Tablets are commonly used with graphical applications, one example using both the pressure and position information is controlling a brush in a painting application. The virtual brush's location is controlled by the physical location of the Wacom pen and the pressure applied to the tip of the pen controls the size of the brush. A physical advantage of the tablet's design is it maintains a fixed two-dimensional working plane similar to the mouse that is well suited to 2D problems.

The Rockin'Mouse [BALA97] is a modified computer mouse with two of its bottom edges rounded to allow tilting operations. A Wacom digitising tablet is employed to capture the additional tilt sensing, around X (left-right) and Z (near-far)) axis, providing 4 DOF. The purpose of tilt sensing is to allow direct 3D manipulations that are not possible using a 2 DOF sensor. Balakrishnan et al. performed an evaluation that measured the efficiency of a 3D positioning task comparing a traditional mouse and the Rockin'Mouse. Subjects were asked to move an object from one corner in a virtual room to the diagonally opposite corner.

[3]http://www.wacom.com/

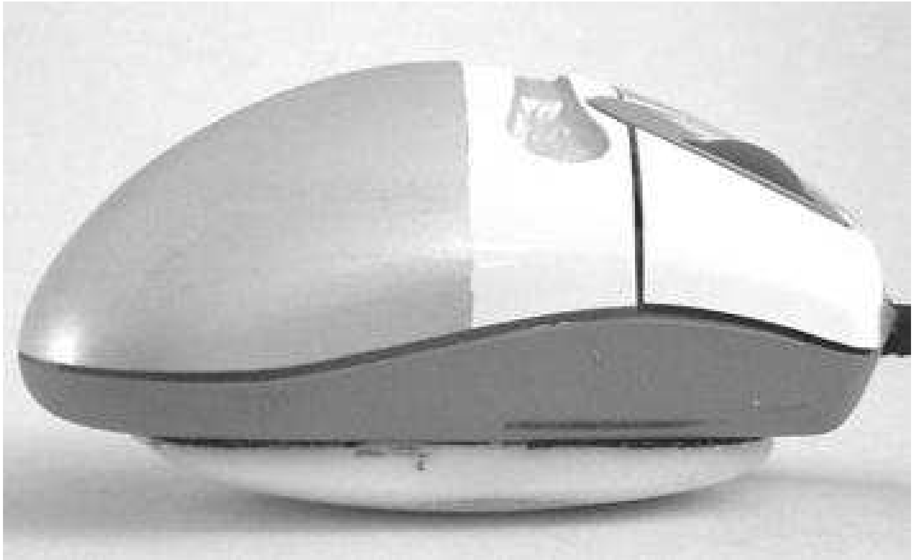


Figure 2.7: VideoMouse, a 3D pointing device with 6 DOF. (Reprinted with permission from Ken Hinckley - Microsoft)

The results showed a 30% increase in performance using the Rockin'Mouse compared to a traditional mouse [BALA97].

Hinckley et al. developed the VideoMouse [HINC99], a tradition mouse modified to accommodate a 6 DOF optical tracking sensor. A CCD camera, LEDs and pattern markers were retrofitted to the base of a mouse (shown in Figure 2.7). A pose estimation algorithm is used to determine the 3D position and orientation of a camera based on the 2D location of known markers [DEME95]. The VideoMouse provides full tracking of the X and Y position, identical to a traditional mouse, and the Z axis provides a restricted operating range from 0 - 3cm. Rotation around the Z axis is unrestricted (0° - 360°), while rotation around the X axis is $\pm 25^\circ$ and $\pm 20^\circ$ around the Y axis. The VideoMouse is an isotonic device providing the functionality of a traditional mouse for normal operation, while new techniques are possible in three-dimensional environments using the 6 DOF tracking capability. Like the Wacom tablets, the VideoMouse requires a flat table surface during operation that maintains a reference plane during operation. Hinckley et al. discuss two clutching techniques for operating the VideoMouse in a 3D environment. Firstly, using the device with 5 DOF for manipulation operations while lifting the device (Z axis translation) is used for clutching gestures. Alternatively, the 6 DOF can be used for manipulations and a keyboard button assigned to clutching.

Spatial Freedom Inc. manufacture a range of isometric spatial controllers (see [SPAT08] for a detailed history), the SpaceBall 3000™ (shown in Figure 2.2(b)) allows navigation and manipulation operations with 6 DOF in 3D environments. It employs pressure sensors to allow separate translation of X, Y and Z and rotations of yaw, pitch and roll. The SpaceCat [SUND09] is similar in appearance to the SpaceBall 3000™, but uses elastic sensors rather than pressure sensors. The handle of the device is suspended with inductive metal springs that allow a unique feel while performing manipulation operations. With the elastic mechanisms, the resistance increases as the handle moves from its original position. The device is also self-centring and similar to isometric devices, and the authors describe rate control tasks as well suited to this device.

The Logitech 3D mouse (shown in Figure 2.8) is a commercially available isotonic device. The Logitech 3D mouse can be used in 2D mode on a flat surface in the same manner as a traditional mouse. Additionally, the user can pick up the device, removing it from the table surface, to perform direct interactions in three-dimensional space. When held above the table surface, this allows a direct spatial mapping between the physical world and the virtual world. Ultrasonic technology is used to calculate the position and orientation of the device. In operation, a pulse is generated at three ultrasonic emitters and received by three microphones attached to the mouse device. The time-of-flight allows a triangulation formula to calculate the position and orientation of the hand-held device (see [SOWI93] for a detailed description).

There are a vast range of pointing device technologies that have explored pointing interactions, a review of additional technologies is described by Kelvin Chen in his PhD thesis

Figure 2.8: Logitech 6 DOF ultrasonic pointing device.

[CHEN08].

For the purpose of this dissertation, the relation between the input device and techniques supported it supports are of particular interest. Three-dimensional pointing devices facilitate intuitive operations in 3D environments by providing a direct mapping to each axis, which is not possible using 2 DOF devices. The SpaceBall ™ and VideoMouse provide 6 DOF allowing translation and rotations to be performed in one operation using a dedicated sensor for each axis. Both these devices have demonstrated benefits within 3D environments by removing the need for mode-swapping techniques required to allow full control of a 3D point in space.

In terms of designing interaction techniques, the input device's functionality (established by the DOF provided by the sensor and the physical shape of the device) determines the type of interactions are possible [FROH00b]. So although the 6 DOF devices overcome some of the limitations of 2D devices, they are restricted when applied to certain tasks. Many physical world tasks require the use of multiple fingers and hands with a high degree of freedom. For example, adding a pinch of salt to a recipe uses both the thumb and forefinger. The salt is picked up between the digits and then the desired quantity is a carefully controlled with friction and a rubbing motion. Kneading dough is another common example that uses all the digits of both hands during operation. These everyday tasks require much more complex tracking mechanisms to capture the actions of the human hand and model complex real world materials in such a complex manner. A number of existing solutions to these problems are discussed in the following sections.

2.2.3 Glove based technologies

A number of whole-hand input technologies are well suited to navigation and manipulation operations in 3D environments. Gloves based technologies capture finger movements and gestures with high degrees of freedom in real-time. Immersion CyberGloves ™ [IMME08] use bend sensors to measure joint angles that capture the finger pose and hand movements. Using CyberGloves it is possible to animate hand movements in real-time. Other designs use fabric switches attached to the glove finger tips [PIEK06a], this design provides less information and is used for navigational tasks such as menu selection or in conjunction with vision tracked markers to assist with modelling operations. Both these designs do not provide any form of haptic feedback an important aspect required for improved performance [DENN00, FELF01, WAGN02]. To overcome this limitation Immersion [IMME08] developed active haptic feedback gloves called CyberGrasp™ (shown in Figure 2.9). These gloves use complex wire based actuators attached to the each of the digits to support computer controlled haptic stimulus. A limitation of this design is they are quite large in comparison to

Figure 2.9: CyberGrasp™ active haptic gloves. (Reprinted with permission from Faisal Yazadi- Immersion Corporation)

the size of the users hands causing restricted finger movements and also donning and configuration of the gloves can be time consuming. For further information on glove based technologies, Dipietro et al. provide a detailed history of glove based literature [DIPI08].

2.2.4 Tracking

Capturing the position and orientation of physical world objects, in conjunction with other input streams such as voice commands, is a widely employed technique to allow human computer interactions. Virtual environments use motion trackers for five primary functions: view control, navigation, object selection or manipulation, instrument tracking and avatar animation (MoCap) [WELC02]. To track the pose of physical world objects a wide range of technologies have been developed including mechanical, inertial, magnetic, acoustic and vision based systems. Survey papers of tracking systems is presented by Zhou et al. [ZHOU08], Welch et al. [WELC02] and Holloway et al. [HOLL93] providing a detailed summary of tracking technologies.

Active magnetic technologies use three orthogonally arranged magnetic transmitters to pulse a magnetic field, which is received by three orthogonally arranged magnetic sensors. With this both position and orientation is reconstructed with a high accuracy (described in

Figure 2.10: Hand motion capture system employing Polhemus sensors attached to a user's fingers. (Reprinted with permission from Kazutaka Mitobe - Akita University)

detail by Rabb et al. [RAAB79]). Polhemus[4] and Ascension[5] produce a range of active magnetic tracking systems, in both wired and wireless designs. Each receptor (transmitter) covers up to 4.7m^2 and can be extended to track larger volumes by using multiple receptors. These systems are particularly robust in appropriate environments however there are a few limitations. Large metal objects cause field distortions affecting the accuracy of the tracker. A functional limitation is imposed by the physical size of the tracking sensors, for example when performing motion tracking of human fingers the large sensor size can interfere with the users. Mitobe et al. constructed a high accuracy motion capture system to track the digits of a pianist in real-time [MITO06]. This system captures fast and complex hand movements allowing virtual hands to move with the same complexity as the pianist (shown in Figure 2.10). The size and complexity of the tracking components needs to be particularly small so as not to weigh down the pianist's fingers, also the size of the wires needs to be considered to prevent tangles. For a system like this to become more usable however, improvements need to be made in the size of the sensors, and to make it wireless.

Vision based systems such as Vicon[6] and IOTracker [PINT08] provide optical systems that employ retro-reflective markers, infrared lights and cameras to track position and orientation in 3D space. Grossman et al. use a Vicon system to support finger gesture interactions

[4]http://www.polhemus.com/
[5]http://www.ascension-tech.com/
[6]www.vicon.com/

with a 3D volumetric display (Actuality Systems[7]). Multiple markers are attached to a user's index fingers and thumb to measure bend operation and the finger tip position and orientation. A series of gestures including: pointing at the display, pinching with index finger and thumb, curling of the index finger, trigger and scrub gestures are used to interact with models on the volumetric display [GROS04, GROS05].

Kato et al. developed ARToolKit a vision based, fiducial marker tracking system [KATO99, KATO99b]. The position and orientation of the fiducial markers is found relative to the camera's location. Tinmith, a mobile outdoor augmented reality system [PIEK02b] employs pinch gloves and ARToolKit markers attached to the user's thumbs to allow human-computer interactions. The tracked thumbs can operate as a true 6 DOF input device, or alternatively as a 2 DOF cursor that can be projected and used for action at a distance. Commercial systems have also used hybrid sensor technologies, for example the InterSense IS-1200 uses both hybrid inertial tracking (similar to the previously described Inertia Cube 3) and vision tracking with fiducial markers to calculate 6 DOF tracking. This system achieves tracking with a 1mm resolution by combining the technologies.

A limitation of the Vicon, IOTracker, ARToolkit and other marker based vision systems is that tracking stops working when markers become occluded. This limitation prevents some close proximity interactions, for example two tracked hands can easily cover each other's markers causing unreliable tracking. In terms of 3D modelling applications, attaching markers (retro-reflective, fiducial, or infrared) to the user's body is also a time consuming and should be considered depending on the task being performed.

2.2.5 Malleable surfaces

Malleable surfaces are pressure sensitive surfaces that capture any deformations of the surface shape. Deformations occur through the touch-point of a finger or any object depressing the surface. Unlike 2D trackpads that use surface area to determine the force of the touch point, malleable surfaces capture a depth value separately from surface area. A number of malleable surfaces have recently emerged that employ a similar vision based technology [KAMI04, VLAC05, VOGT04, SAGA07, MILC06]. To capture the surface geometry information, a camera is installed underneath a silicon membrane with dots printed or attached to its surface (shown in Figure 2.11). When the surface becomes deformed, the location and shape of the dots changes and is used to reconstruct the silicon's surface shape in software (shown in Figure 2.12). Vogt et al. [VOGT04] suggested malleable surfaces may be employed as an input device for 3D modelling operations such as sculpting and mas-

[7] www.actuality-systems.com

sage techniques. Tactex[8] is a commercially available pressure sensitive surface with similar functionality. It employs an array of coplanar optical intensity sensors that allows real-time pressure information to be gathered.

Tabletop technologies have also recently incorporated the functionality of malleable surface technologies. Vlack et al. describe the initial use of their Gelforce silicon surface for use with desktop applications employing visual effects on a tabletop surface [VLAC05]. Recently the Frustrated Total Internal Reflection (FTIR) table design [HANX05] was augmented with a silicon surface [SMIT07a]. This changes the feel of the previously rigid surface to a soft surface that users can push into. A finger painting application was employed and described as well suited for young children. Using this soft table-top surface and the Finger-paint Plus application [SMIT07a] users can paint with their hands, paint brushes, stamps, cookie cutters and other objects in a collaborative painting environment.

Malleable surfaces are a relatively new computer input device and have not been used extensively for interactions in 3D environments. As the technologies become commercially available it is likely the interaction techniques developed will allow new interactions to be performed in these environments. These surfaces do not operate like traditional input de-

[8]http://www.tactex.com/

Figure 2.11: Camera viewing the underside of a malleable surface. (Reprinted with permission from Florian Vogt - The University of British Columbia)

(a)

(b)

Figure 2.12: Malleable surface operation: (a) User manipulating a malleable surface. (b) Camera view of user manipulation. (Reprinted with permission from Florian Vogt - The University of British Columbia)

vices, they provide a data stream with an array of pressure sensor information at high update rates. So unlike pointing devices and tracking technologies their DOF is based on the resolution of the device. Milczynski et al. describes the surface reconstruction as two components, firstly a two-dimensional vector is calculated based on the marker's image position and secondly a depth vector is calculated for each marker using the corresponding Voronoi cell area [MILC06]. This class of devices, functionally allows more than one person to interact with the surface at one time given the working area is large enough. Users can also use multiple fingers to express complex operations such as multi-fingered gestures like pinching. These surfaces are relatively immature and research is required to better understand how they can be exploited to leverage the data streams they provide.

2.2.6 Special devices

The research prototypes presented in this section focus on the development of the technologies designed to solve task specific problems. The devices in this section explore sensing techniques that facilitate a variety of two-handed, whole-handed and multiple finger supporting sensors. These devices have been created for a range of different disciplines and are employed to solve tasks accordingly. Of particular interest to this dissertation are device that facilitate modelling techniques such as sculpting or clay like interactions.

2.2.6.1 ShapeTape™

Using traditional devices to sketch curves in three-dimensional space is well established [BANK90, COHE99] and have contributed to the development of devices that capture physical gestures. Baladrishnan et al. demonstrated the capture of two-handed gestures to manipulate a commercially available sensor called ShapeTape™ [BALA99] (shown in Figure 2.13). Rather than using mathematical functions, a computer mouse and a traditional CAD environment, they are exploring the use of ShapeTape™ to express curved shapes. ShapeTape™ is a flexible tape made of rubber, a steel spring and a optical bend sensors. Their system incorporates a 6 DOF tracker and 4 buttons (for clutching) attached to the ShapeTape™. A foot operated mouse is also used to control the scene and camera view. A number of interactions were presented including basic curves, surfaces made of profile curves (loft), a revolving technique allowing a profile curve about a give axis and extruding of a volume. When modelling with ShapeTape™ both hands and multiple fingers can manipulate the physical shape which is captured accurately on the virtual model. The authors explain that the intuitive use of the device allows shapes and effects to be quickly obtained [BALA99, GROS03].

2.2.6.2 Cubic mouse

The Cubic Mouse [FROH00a] is a hand-held input device with a total of 12 DOF, three 2 DOF tracked rods that protrude out of the faces of a cube and 6 DOF tracking to allow registration with a virtual environment (shown in Figure 2.14). Users push and pull on the rods that correspond with the X, Y and Z axis in the virtual world. Fröhlich et al. discuss a demonstration application that uses virtual orthogonal cutting planes controlled with the rods of the Cubic Mouse, to visualise a volumetric data set. In their demonstration a user can explore the internal data of a computed tomography scan of a human head. Two-handed operations are required to use the device and some users found the overall size a little too large (9cm x 9cm x 9cm). The functionality of this device sets itself apart from a other 2 DOF devices like a mouse because it removes the need for mode-swapping when specifying three-dimensional coordinates in applications. Additionally the entire device can be registered with a virtual would using the 6 DOF position tracking sensor. The cubic mouse was also later commercially produced by FadeSpace[9] with 3 optical rods (25.4cm each in length), 6 DOF tracking, twelve programmable buttons and a RS232 serial interface for communications.

[9] http://www.facespace.com/

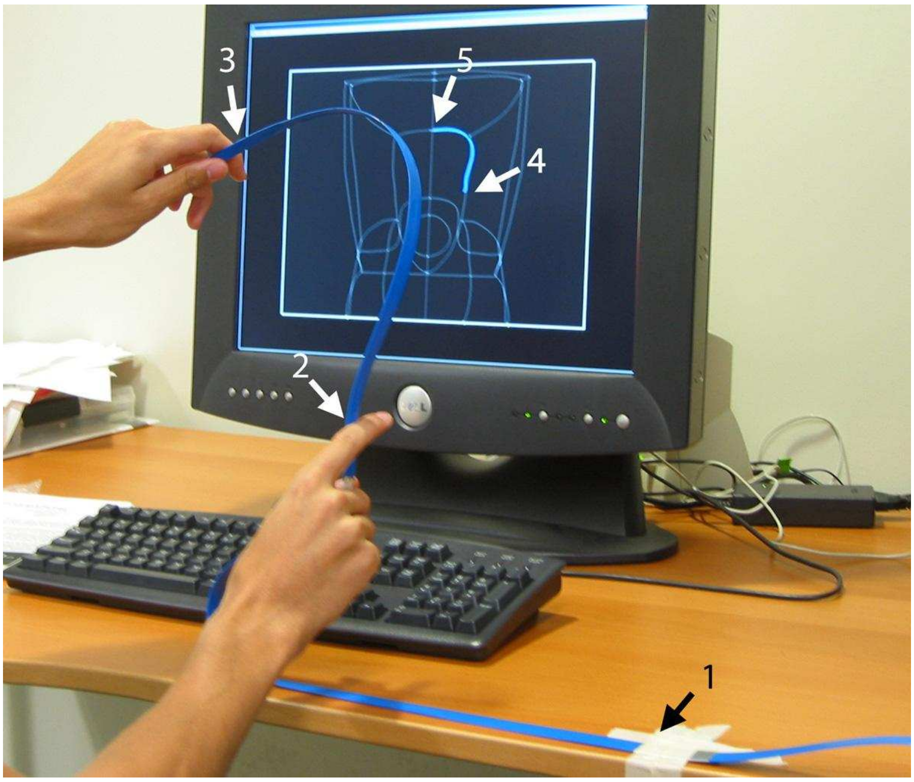


Figure 2.13: Curve modelling with ShapeTape™ (Reprinted with permission from Tovi Grossman - University of Toronto).

2.2.6.3 Phantom

The Personal Haptic Interface Mechanism (Phantom) is an active haptic feedback device that measures both a precise fingertip position and exerts a computer controlled force on the finger tip as required [MASS94]. Massie et al. describe three important criteria considered for the design of the Phantom, firstly the type of haptics senses their device targets is those that allow humans to perceive and rearrange objects in the real world. They describe the kinaesthetic, force and cutaneous senses in conjunction with motor control senses that support human perception. Also identifying the importance of the spatial and environmental mappings human fingers provide during physical exploration. Secondly, in their original design the "thimble-gimble" provides a passive 3 DOF mechanism capable of capturing finger tip interactions. Thirdly, the working volume of their device was selected based on an experiment that determined the volume a user required to move their wrist without encountering the edges of the workspace. With the original design a single point in three-dimensional space is used, more recently the Phantom design has adopted up to 7 DOF allowing pinch operations

Figure 2.14: The Cubic Mouse a 12 DOF input device. (Reprinted with permission from Bernd Fröhlich)

to be captured using either a scissor or thumb-pad effector[10]. Multiple Phantom devices can also be used in parallel to provide multiple-finger interactions [WILL03] [MICH02].

The Phantom is now a commercially available device produced by SensAble Technologies[11], and is regularly employed in Virtual environments, allowing real-time interactions with virtual objects [KENN97, MCDO01, FISC03]. Pihuit et al. extended the functionality by attaching a ball with five pressure sensors to a Phantom haptic arm [PIHU08]. This device was used to model a virtual hand allowing sculpting interactions with virtual clay application (shown in Figure 2.25).

2.2.6.4 Two - 4 - six

The "two - 4 - six" is a hybrid input device [KULI06] that employs inertial gyroscopes for orientation, an elastic sensor for translations and an isotonic 3 DOF touch-pad for rotations

[10] http://www.sensable.com/
[11] http://www.sensable.com/

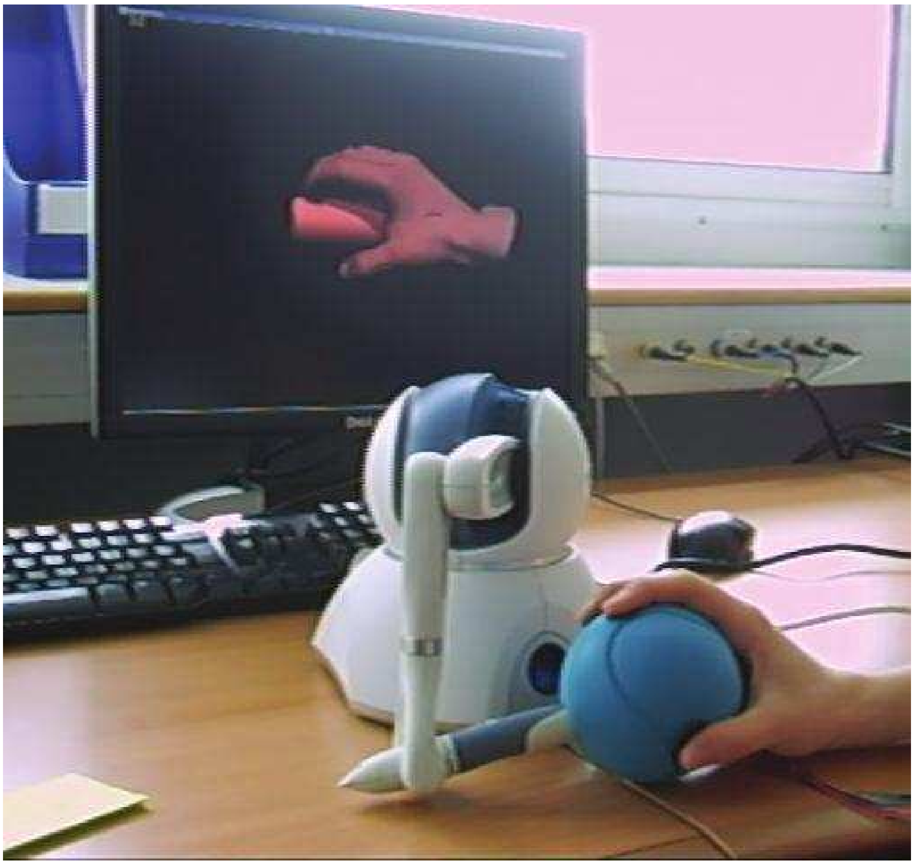


Figure 2.15: Phantom haptic device with five pressure sensors attached to grip allowing virtual clay sculpting. (Reprinted with permission from Adeline Pihuit - University of Grenoble and INRIA)

(shown in Figure 2.16). The “two - 4 - six” device is designed to allow a presenter to navigate through a three-dimensional slide with the one-handed input device. To travel through the world the presenter physically points the device in the direction of desired flight. Sliding movements parallel to the two-dimensional image plane are achieved using the outer elastic ring. And rotations are performed using the inner isotonic touch-pad. The spatial design of the device was designed to support the specific task of performing a presentation allowing the performer to easily navigate a three-dimensional environment with one handed interactions.

2.2.6.5 Tango

The Tango [PAIX05] is a spherical shaped hand-held input device (Shown in Figure 2.17(a)) that measures the distribution of pressure applied to it’s surface. Two hundred and fifty six capacitive analogue pressure sensors are employed on the device’s surface and it is also equipped with a 3 axis accelerometer. To provide a mapping between a virtual hand and the Tango input device a customised Kalman filter [HADD76] was employed to extract 11 DOF and used to update the position of a virtual hand. Kry et al. used the Tango device to perform motion capture and applied it to animation of the human hand [KRYX06]. Their interaction technique uses the contact locations of the force sensors, and motion of the device in free-space to estimate joint compliance (the inverse of stiffness). Pai et al. describe their goal is to explore input devices and techniques that afford manipulation of 3D models in a natural

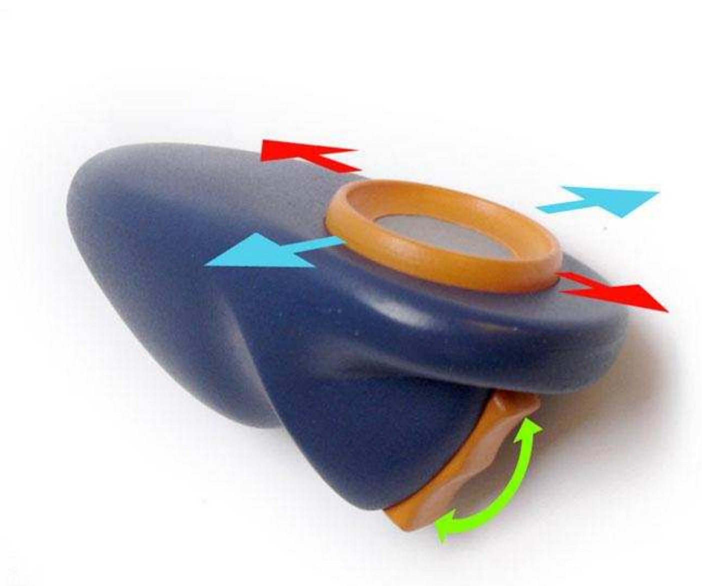


Figure 2.16: Two - 4 - six hybrid input device. (Reprinted with permission from Alexander Kulik - Bauhaus University Welmar)

way [PAIX05].

2.2.6.6 iSphere

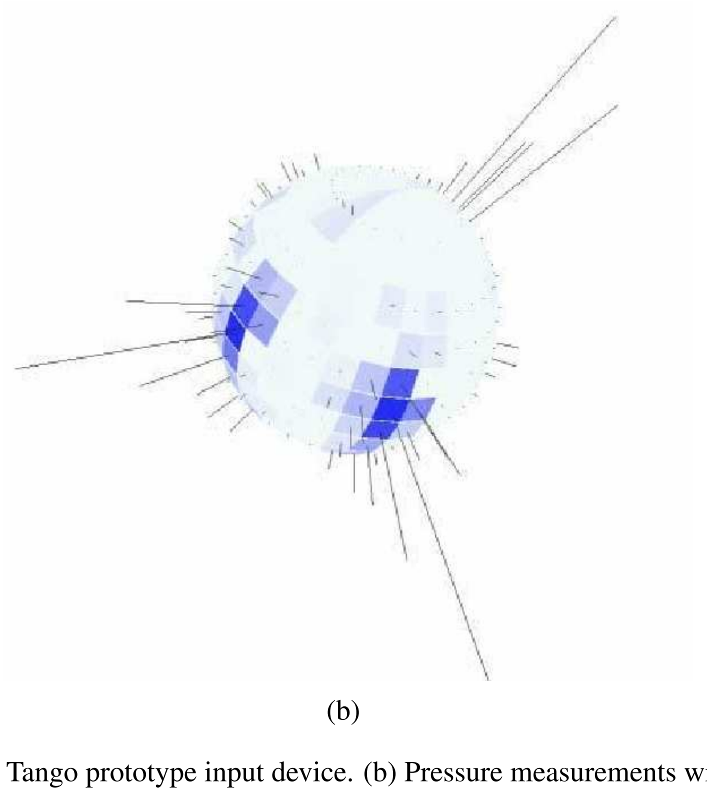
Chia-Hsun et al. presented the iSphere [LEEX04], a dodecahedron shaped input device with each of the twelve faces incorporating a proximity based capacitive sensor (shown in Figure 2.18(a)). The iSphere allows 3D modelling interactions based on the proximity of the user's hands, a pushing operation is performed when closer and a pulling operations when further away. A foam material was added to the surface of the dodecahedron (shown in Figure 2.18(b)) to provide a passive haptic feedback when in range of the proximity sensors. To improve the performance of the proximity sensors a reference signal is transmitted through the user's body providing up to six inches (15.24cm) range on each sensor. A pilot study was performed to identify how iSphere would perform clay-like modelling operations in comparison to a keyboard and mouse. Subjects were asked to perform simple 3D modelling operations using the iSphere and traditional desktop input using Maya. It was observed when using the keyboard and mouse, the thinking time before starting the task was greater than with the iSphere. Also, during modelling, the iSphere allowed multiple vertices to be modified simultaneously unlike the sequential operation of the keyboard and mouse approach. The iSphere offers a unique approach to free-form modelling, there are however limitations in its current prototype stage. The sensing technology does not require electronics to be attached to the user's hands, like with pinch gloves, but the user is still required to sit on a metal strap to provide adequate proximity sensing. Also the resolution of the device is limited with only twelve points of interaction [LEEX04, LEEX05, LEEX06].

2.2.6.7 Volflex

Volflex [IWAT05] is an input device constructed of a group of air filled balloons bound together with a stretchable netting (shown in Figure 2.19). Pressure sensors on each balloon detect user applied forces, while the computer inflated balloons can alter their pressure according to the material being modelled. Virtual clay properties can be rendered in real-time on the Volflex device using projected information.

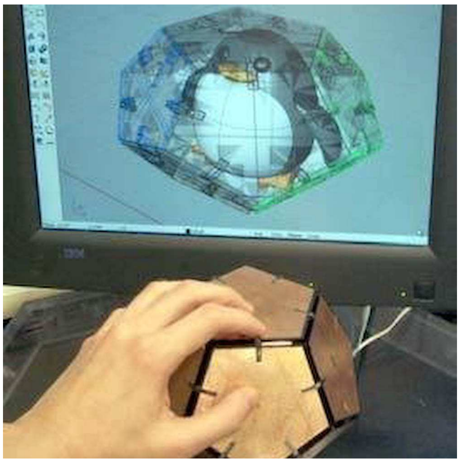
Although prototypes such as this are immature, they are very promising 3D modelling tools. They combine an active shaped volumetric surface with real-time display technologies. As algorithms are developed to control such devices and the resolution increases, these devices are capable of capturing the complex multi-fingered gestures humans use everyday in the physical world. This allows for a new range of interaction techniques within 3D environments, reducing the gap between abstract mathematical and everyday human interactions.

(a)

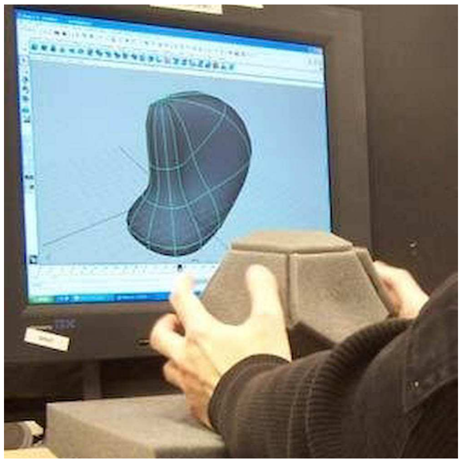


(b)

Figure 2.17: (a) Tango prototype input device. (b) Pressure measurements with a three finger grasp. (Reprinted with permission from Dinesh Pai - University of British Columbia)



(a)



(b)

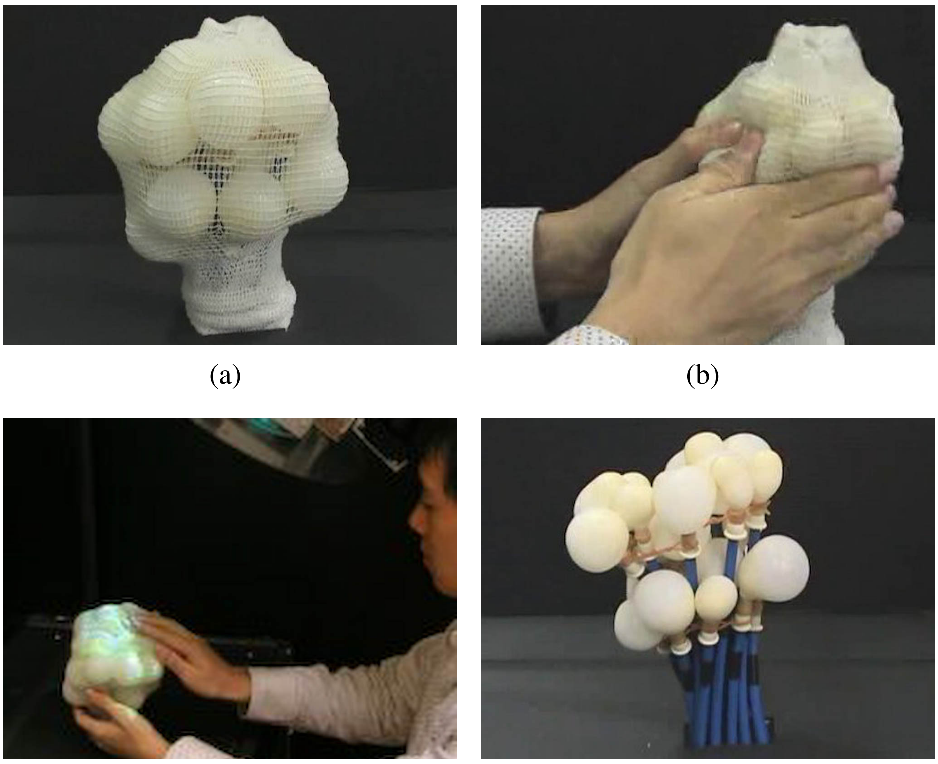
Figure 2.18: (a) iSphere input device. (b) Foam added to the surface of iSphere providing passive haptics. (Reprinted with permission from Chia-Hsun Jackie Lee - Massachusetts Institute of Technology Media Laboratory)

2.2.6.8 Senspectra

Senspectra developed by LeClerc et al. [LECL07] is a device made up of configurable nodes and joints (seen in Figure 2.20). It is designed to capture and present visualisations of structural strain. This information is used to perform structural engineering analysis with the benefits of a tangible user interface that is capable real-time sensing of deformation made to the Senspectra prototype. In the current form the prototypes uses a number of quite large nodes that are illuminated with LEDs to show the stress of the attached joints. Organic shapes can be designed by the user which is detected by the sensor and displayed as a 3D model visualisation. This system provides an example of a less-rigid material used for a computer input device. In the current form, fine grained finger interactions can not be captured using this technology, for example capture a pinch gesture is not possible.

2.2.6.9 Conductive foam sensors

There are a limited number of reported uses of input devices that use conductive foam as a resistive sensor [MURA94, DUNN06]. Murakami et al. constructed a non-conductive foam cube with conductive foam strips attached to its surface (Figure 2.21). The conductive foam strips are used as length sensors, i.e. a user may deform the device by squashing it with their hands and the length sensors are used to measure deformations. The performance of the foam sensors was indicated to be somewhat inaccurate, the authors state “Because of the inaccuracy of the conductive foam as a sensor, measured lengths can be geometrically



(a) (b)

(c) (d)

Figure 2.19: (a) Volflex shape changing input device constructed with a group of computer controlled, air filled balloons. (b) User altering the surface shape using a two-handed sculpting-like manipulation technique. (c) Projected graphics on the material sheath. (d) View of balloons with sheath removed. (Reprinted with permission from Hiroo Iwata - University of Tsukuba)

impossible”. However, the node positions of their model can be determined at the converged position even with inaccurate length measurements [MURA94]. In their implementation the manipulation of a wire-frame model is achieved through pressing, bending and twisting the device to create a basic shapes.

Dunne et al. employed conductive foam sensors in a garment based technology [DUNN06]. Polypyrrole [BRAD05] coated foam is embedded into a garment near the shoulders, and the sensors are used to detect movement events. The authors reported: ”Results indicate that while the sensor performs well when detecting simple movement events (a switch-like interface), there are challenges to overcome in coordinating the responses of multiple sensors in more fine-grained interaction tasks” [DUNN06].

Little research has been performed into the design of conductive foam based sensors and input devices, however the foam medium provides an interesting tactile response that can be leveraged to assist with modelling operations. This dissertation explores and extends the use of conductive foam sensor as described in the commencing chapters.

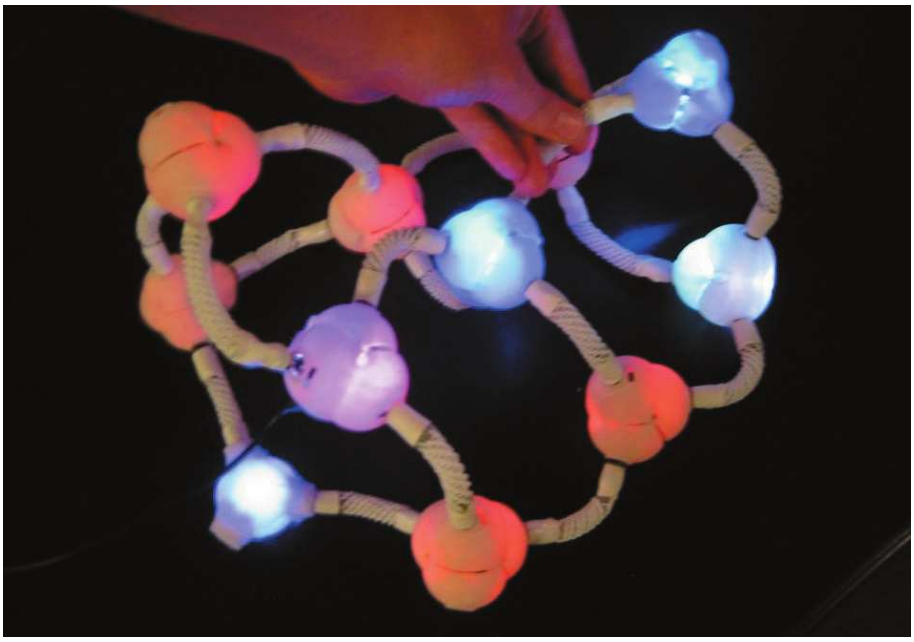
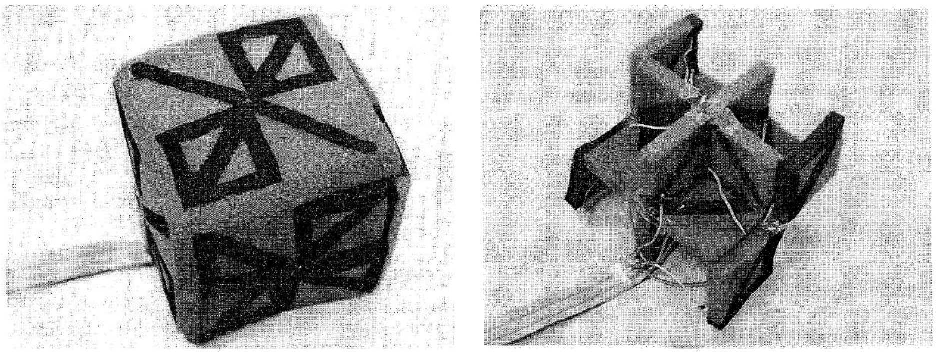


Figure 2.20: Senspectra: A device for capturing structural strain that uses reconfigurable joints and nodes. (Reprinted with permission from Hiroshi Ishii - Massachusetts Institute of Technology Media Laboratory)



(a) (b)

Figure 2.21: (a) Cube shaped conductive foam input device. (b) Inside structure of input device. (Seeking permission)

2.3 Input device philosophies and design characteristics

Ideal input devices allow the user to express exactly the information required for the application, neither more nor less [MACK90]. Mackinlay et al. present design guidelines based around their taxonomy of input device properties. A case study is presented following the metaphor of a human walking around a room, their high level design process is as follows: "(a) identify application functionality, (b) assign input devices to the application's parameters in a manner consistent with the expressiveness criteria, and (c) compose these devices together in a manner consistent with the expressiveness criteria" [MACK90, CARD91]. This dissertation is interested in a number of semantic issues for 3D environment navigations and manipulation that are discussed in this section.

2.3.1 Desktop and mobile environment requirements

Common desktop environments provide a fixed horizontal surface, an important aspect for using a mouse and keyboard. The fixed position of the keyboard provides a predictable tactile response. For example, it is difficult to use a keyboard that is sitting on your lap because it moves around while typing and most mice require a planar surface for the sensors to operate correctly. Although these two devices necessitate a flat surface, not all desktop input devices have the same requirement. Pinch gloves, for example, might be employed for modelling at a desktop system but are also well suited for mobile environments. Some environments, such as a cave automatic virtual environment (CAVE), allow a user to walk around freely and thus have different input device requirements compared to desktop environments. This is because the convenience of the table's flat surface is no longer available and other technologies need to be employed in place of the keyboard and mouse. Although there are specific requirements for desktop and mobile environments, this is not to say that some input devices can not be used in both. Pinch gloves or hand-held trackballs might be employed in either environment.

2.3.2 Device mappings

The mapping from the input device to the software application affects the human computer interaction performance. A mouse to cursor is an example of a well matched input device to application. The mouse has two merged orthogonally mounted position sensors providing a relative X Y position that are mapped to a two-dimensional slider, the cursor. Mackinlay et al. describe in detail their input device taxonomy and syntax to describe the connections between devices and application parameters [MACK90]. For a two-dimensional desktop pointing device it is difficult to improve on the design of the mouse [ZHAI95]. However, three-dimensional input devices have evolved much slower and due to the popularity of the mouse application developers have adopted techniques that map the 2 DOF position to three-dimensional manipulation and navigation operations.

2.3.3 Multiple touch point and finger interactions

Multiple touch-point technologies have been around since the early 1980s [MEHT82, BUXT07]. These technologies are different compared to traditional touch screens because they are capable of reporting the touch-point of multiple locations simultaneously. By capturing the additional touch-point information multiple fingers can be used to perform gestures to instruct a computer system. Early research into finger based gesture recognitions were performed by Krueger with his VIDEOPLACE system [KRUE85] and Wellner with the DigitalDesk [WELL91]. These systems demonstrated two-fingered scaling and translations of objects employing an augmented reality environment. Recently, this functionality has been incorporated into commercially available products such as the iPhone that uses similar two-fingered gestures.

In terms of input device design, the existing literature supports new input designers to leverage complex finger interactions for a number of reasons. Zhai et al. evaluate the influence of muscle group performance in relation to 6 DOF input devices. Human fingers relative to other parts of the human body are well represented by the motor and sensory cortex. Formally a homunculus diagram describes this relation [SAGE71], Figure 2.22 provides a sculpted artistic representation that describes the ration of the cortex if each part of the

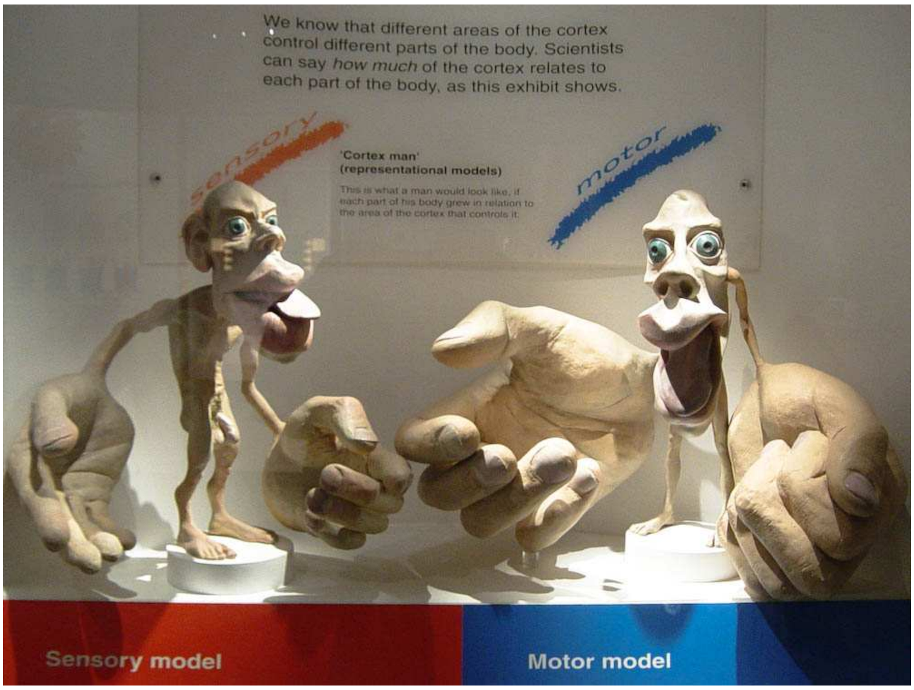


Figure 2.22: Artistic sculptures describing the ration of the cortex function. The left figure describes the somatosensory and right the motor cortex. (Photograph taken at the London Science Museum - Public Domain)

body grew to the relative area of the cortex that controls it (as discussed by Zhai [ZHAI96] in the evaluation of the of the FingerBall and the MITS Glove previously discussed in section 2.2.6). The concluding remarks in this study discuss the performance advantages that can be achieved by using input devices that are manipulated by the fingers have performance advantages over operating devices with the wrist, elbows and shoulders. Their results comparing the performance between the MITS Glove and FingerBall supported these statements. Finally they suggest "The results of our study strongly suggest that future designers of such input devices should design the affordances of input devices (i.e. shape and size) such that the fingers are included in their operation to whatever extent is feasible." [ZHAI96].

2.3.4 Affordances and epistemic actions

The term affordance was introduce by Gibson and is defined as "all action possibilities latent in the environment, objectively measurable and independent of the individual's ability to recognize them, but always in relation to the actor and therefore dependent on their capabilities" [GIBS77, GIBS79]. For example, a door handle may indicate from its shape if one should push or pull on the door to open it.

The term affordance used in a HCI context describes action possibilities which are perceivable by an actor [NORM88]. For example, Donald Norman who adopted the term for use in HCI presents the example "a chair affords ("is for") support and, therefore, affords sitting". Applied to interaction design, a number of researchers [HINC94, JUXX03, HEND08] have adopted the physical input device design considering affordance. Henderson et. al [HEND08] describe a technique that leverages existing affordances with in the environment to provide a passive haptic sensation for AR applications. Figure 2.23 shows the use of a virtual slider in an AR environment where the groves in a wiring harness are used to provide a passive haptic sensation.

In HCI often the efficiency, effectiveness and satisfaction of an interface is measured to perform an quantitative assessment. Recently, as tangible user interfaces (TUIs) are becoming a area of developing research, a fourth metric known as epistemic actions is being explored as a possible metric. An epistemic action is "an action where by users change their environment to search for a solution or strategy to perform a certain task rather than to move closer to an external goal state" [FJEL09]. Fjeld et al. performed an experiment with three environmental setups, one entirely virtual, one with no physical interaction, the second with some physical interaction and the last with entirely physical interactions using TUIs. In their initial result they actually found that the number of epistemic actions was actually lower with the environments using physical interactions. The authors have suggested that the "trial-and-error" actions used when manipulating TUIs provides a non-linear measure for cognitive

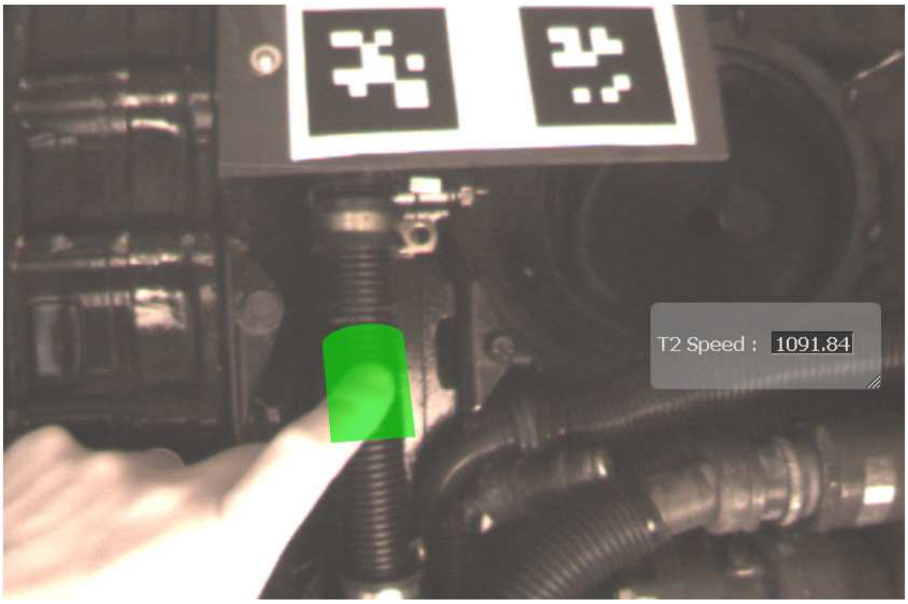


Figure 2.23: Example of environmental affordance employed for passive haptic feedback. The groves in a wiring harness are used to help position a virtual slider. (Reprinted with permission from Steven Feiner - Columbia University)

support and that perhaps it is limited to task specific domains.

2.4 Interaction techniques

Interactions performed in three-dimensional environments commonly include: navigation, object selection, command entry and manipulation. This section describes interactions with a focus on research that has presented virtual sculpting or clay modelling techniques.

2.4.1 Menus

Numerous menu and navigation techniques have been used in Virtual and Augmented Reality systems. Blaskö et al. developed a pull down menu interface for wearable computing [BLAS02]. A user can select hierarchical menu options by running their finger along either the horizontal lower edge or predefined vertical strips of the touchpad. Bowman et al. used pinch gloves to control their TULIP menu system [BOWM01]. Menu items are mapped to each finger in the virtual environment. Circular menus have been employed in virtual environments. HoloSketch [DEER95] uses a 3D pie menu with concentric menu items that can be activated with a wand. Liang et al. presented the JDCAD 3D modelling system [LIAN93] that uses a spherical and ring menu for object selection. The idea is further

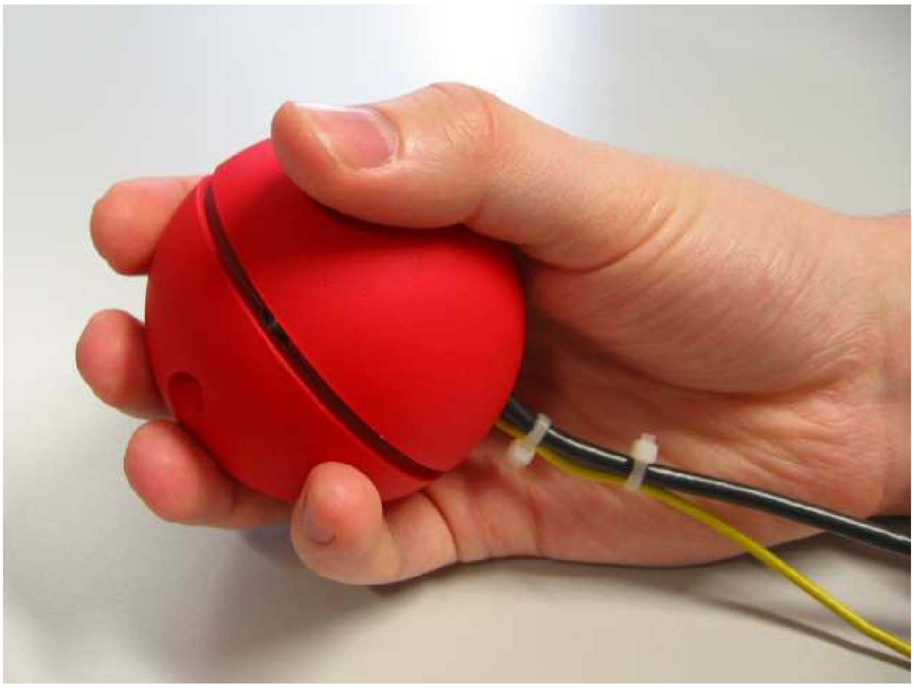


Figure 2.24: iOrb hand-held input device for mobile augmented reality applications. (Reprinted with permission from Gerhard Reitmayr - Vienna University of Technology)

evaluated and developed by Gerber and Bechmann [GERB04, GERB05] into a hierarchical spin menu as a context menu in a VR environment. Shomake presented the Arcball input technique [SHOE92] allowing a intuitive mathematical mapping between a 2 DOF mouse to control rotation and three-dimensional interactions.

Reitmayr et al. presented the iOrb [REIT05], a hand-held input device that tracks orientation (shown in Figure 2.24). The input device employs an InterSense InertiaCube 2 installed into a custom built spherical shaped body. The device is used to control menu operations by firstly mapping three orientation values to a 2D coordinate system with orthogonal axis based on the user's current arm pose. These values are then mapped to different menu widget styles. Two selection methods were used, one uses a time-out value and the second uses a predefined threshold angle allowing menu selection operations. Zhai et al. performed an experiment with a similar shaped device that incorporates a 6 DOF tracker, called the FingerBall [ZHAI96]. The user evaluation compared the performance of the FingerBall to their 6 DOF MITS Glove [ZHAI96] and measured that while performing a docking task (aligning a 3D cursor with a target) the FingerBall manipulation times were faster. With the FingerBall, a user can shuffle the device between their fingers allowing flexible control. They concluded that affordances such as shape and size should be carefully considered so as to leverage the dexterity of the human fingers.

2.4.2 Modelling systems

Early free-form modelling techniques presented various control point manipulations techniques, these systems allow various deformations of geometric models including bending, twisting and tapering operations to be performed [SEDE86, GALY91, WELC92, LAMO94]. Since these early pioneering systems explored clay and sculpting like manipulation interactions using keyboard and mice as the primary control device a number of have explored using 3D input devices to provide more intuitive operations and spatial mappings between the physical environment and virtual models.

Many 3D surface manipulation techniques have been developed to support artistic and intuitive user interface techniques. JDCAD developed by Liang et al. is an example of a early desktop system that allows three-dimensional primitive shape creation and reshaping operations [LIAN93]. There are a number of problems relating to the control of 3D scenes with 2D input devices describing the unnatural mappings required to facilitate modelling operations. To overcome these problems their JDCAD system employs a 6 DOF head tracker and the bat (a 6 DOF hand controller) allowing three-dimensional interactions. To create a model, the user first select a base shape, such as a cylinder, from a ring menu and uses a bounding-box selection technique to stretch the shape to the desired size. Reshaping 3D models using existing 2D manipulation techniques where handles are placed around the edges of a shape to allow manipulation are described. The problem with this approach is that on a complex 3D shape, the handles significantly clutter the screen. To overcome this problem, the use of invisible handles and the use of various regions around the shape are allocated to a range of reshaping function indicated by the cursors shape.

Virtual Clay [MCDO01] is a VR system that provides an interactive free-form modelling environment. McDonnell et al. also developed an interactive sculpting framework that encompasses modelling techniques based on the subdivision of solid geometries. It supports clay like manipulations allowing intuitive sculpting to be performed with physics based responses and haptic feedback using a Phantom device [MASS94].

Schkolne et al. [SCHK01] used Cygber Gloves and the Responsive Workbench [KRUG94] to create a free-form 3D modelling system. Their system "Surface Drawing" tracks the user's hand locations and Cyber Gloves to allow stroke based drawing to be performed. This system is of particular interest as it is designed to support creative expression in a three dimensional space. Their techniques allow sketching by tracking a user's arm location and hand pose. The authors compare creating a stroke in 3D space to drawing a line on a piece of paper.

Jung et al. completed a field study observing artistic modelling techniques including CAD, clay modelling, wood carving and glass crafting [JUNG04, JUNG05]. They observed these techniques to conceptualize and develop Spray Modelling. Spray Modelling uses a

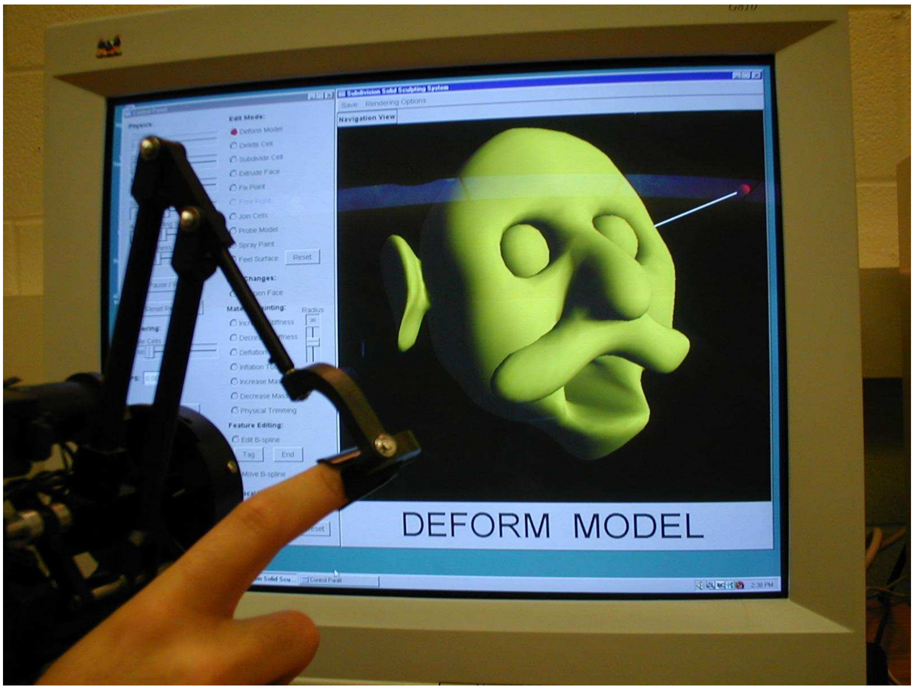


Figure 2.25: Phantom haptic device performing virtual clay sculpting. (Reprinted with permission from Kevin McDonnell - State University of New York at Stony Brook).

tracked physical spray gun as a tangible prop. Models are created in three steps, an initial 3D frame drawing, volume spraying, and air spraying for smoothing.

Commercially available tools such as AutoCAD, Maya and ZBrush provide a 3D modelling environment for desktop systems. In comparison to traditional desktop CAD systems the ZBrush ™ environment is well suited to clay-like sculpting operations. ZBrush was first demonstrated at SIGGRAPH in 1999. The technology represents 3D models using a primitive called a pixol. Pixols are similar to pixels and voxels, a pixel (picture element) is the smallest piece of information in a two-dimensional image, colour LCD screen pixels are usually made up of a red, green and blue component. A voxel describes a volumetric element in three-dimensional space with a constant value for volumetric data. A voxel data set might use a 10 x 10 x 10 data set to represent volume in space. A pixol incorporates two-dimensional pixel information with additional depth and shading information (so unlike a voxel it is not a true three-dimensional volume).

2.4.3 Geometry capture

There are a number of different techniques that have been used to capture physical geometries. A common technique is to measure the physical object and manually enter dimensions. More recently, commercially available laser scanners [POLH07] allow the capture of complex geometries with a high polygon count. These scanners are not designed for real time manipulation tasks and corrections are usually needed to correct captured models. The Façade system [DEBE96] uses a number of photographs taken from different angles; these are processed manually to create a reconstruction of the geometry. The Tinmith system uses pinch gloves and fiducial markers to track a user's thumbs allowing a range of CAD-like interaction techniques including construction at a distance, AR working planes, infinite carving planes, orthogonal laser carving, and surface of revolution as described in [PIEK04b] using AR.

Commercially available stereo cameras, such as the Point Grey Bumblebee®2[12] can also be used to capture three-dimensional images. A stereo camera is constructed with two cameras that find the intersection of rays cast from the cameras multiple viewpoints allowing a depth image to be created [POIN08]. Recently a new sensor has emerged that captures both colour values and distance z-data from a single camera. 3DV systems[13] produce the ZCam™ a Red Green Blue and Z depth (RGBZ) camera that operates at up to 60 frames per second, with a depth resolution of 1cm - 2cm and an operating range of between 0.5m and 7m. RGBZ cameras calculate the additional depth information by pulsing infrared light and measuring the time it takes to return, near objects have a shorter return time compared to objects at a further distance [RGBZ08].

2.4.4 Tangible user interfaces

A tangible user interface supports manipulation of digital information by using the physical environment. The ideal TUI provides a seamless extension to physical objects into the physical world [ISHI97]. Hinkley et al. employed physical props to support neurosurgical visualisations [HINC94]. A physical dolls head and flat piece of plastic were used to represent a CT scan of a 3D skull and cutting plane model (shown in Figure 2.26). Attached to each of the physical props is a Polhemus 6 DOF sensor providing real-time tracking. This allowed a user to explore the complex inner geometry details of the skull model by manipulating the physical props [HINC94]. This system provides a demonstration of how tangible props can provide an intuitive user interface based on physical world affordances.

Ishii et al. presented the metaDESK, a pioneering system, employing phicons (physical icons) with the goal of bridging the gap between the physical and digital worlds. Using optical, mechanical and electro magnetic sensors the icons and display surface work in synchronisation. For example, scaling the size of a digital window can be performed by moving

[12] http://www.ptgrey.com/
[13] http://www.3dvsystems.com/

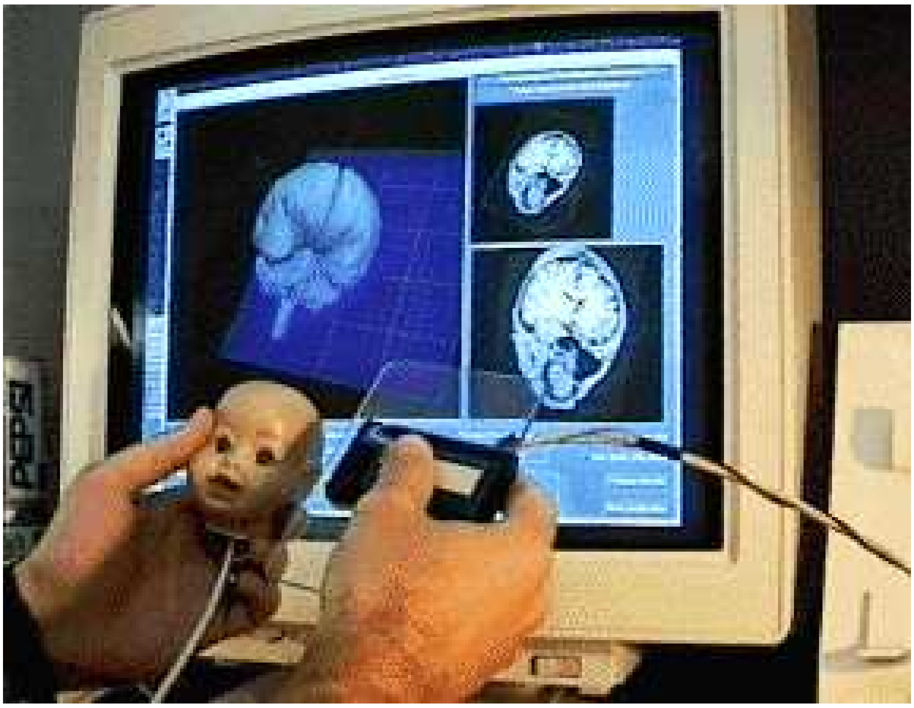


Figure 2.26: A dolls head and plastic plane used as tangible props providing an intuitive input device affordance. (Reprinted with permission from Ken Hinckley - Microsoft).

physical devices on top of the display surface. Their systems incorporate the use of projectors and an activeLENS (an arm mounted flat panel display) to further merge the physical and digital worlds [ISHI97].

Kojima et al. presented the augmented coliseum system, an augmented reality technology that employs tangible, computer controlled robots with a real-time action game. Players control the robots with either hand-held controllers or can physically pick the robots up with their hands. A projected table surface provides graphics for game play and additionally supports an optical tracking system developed find the robots location in real-time. Five photo diodes detect a projected pattern with varying light intensity to calculate both a 2 DOF X Y position and orientation around the Z axis [KOJI06]. Furuhira extended this system to use an LCD display in place of the projector overcoming occlusion limitations. The robots were miniaturised in the later system allowing them to be easily hand-held (shown in Figure 2.27). Additional touch switches added to the robots also allowed users to perform command entry during operation.

Figure 2.27: Miniaturized hand-held robots that support active tangible interactions.

2.4.5 Three-dimensional environments

To date, 3D environments are used in both commercial and research fields for applications such as CAD, entertainment systems and simulated training scenarios. The concept of using a computer to generate artificial stimulus was first proposed in 1965 by Ivan Sutherland with his paper "The Ultimate Display" [SUTH65]. He described a display connected to a computer that would allow humans to visualise phenomena we can not see with the naked eye, such as electrons. Today much of his vision is reality, many homes are equipped with computers and displays capable of providing the "looking glass into a mathematical wonderland" [SUTH65]. Desktop, virtual and augmented reality systems all provide a means of generating simulated computer environments each with their own benefits and disadvantages. The hardware and physical environments require to support these environments varies significantly as do the tasks they are used to perform. A definition, description and example of each is provided for each.

Desktop environments are set up to be used in one location and do not allow users to move around during use. The display of desktop systems is not physically registered with the users body, unlike an immersive virtual reality system with a HMD, and the surrounding environment is usually visible. Additionally, head movements are usually not tracked to control view point of the three-dimensional world.

Brooks defines virtual reality as any experience "in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint" [BROO99]. Immersion is the state of consciousness where an immersant's awareness of physical self is diminished or lost by being surrounded in an engrossing environment; often artificial [NECH99]. Often the immersion level is used to distinguish between desktop systems and immersive virtual reality environments. Games and other three-dimensional worlds employed on desktops computers are virtual reality systems, however, the level of immersion of desktop systems is not the same when using a HMD and a tracked head position for viewpoint control.

Augmented reality is the process of combining computer generated graphics that are registered with physical world view [AZUM97] [AZUM01]. Augmented reality technologies are either hand-held or immersive hardware systems.

All of these environments provide rich 3D interactive systems that have previously not been readily accessible. As computing power has increased and become readily available to the commercial and public domains there has been increased demand for interaction methods that optimise efficiency of common tasks.

2.5 Summary

Input devices are an essential component allowing an interface between the real world and computer systems. While the computer mouse is prevalent and is likely to remain the pointing device of choice [ZHAI95] and the keyboard the device for text input, pointing and text entry are only some of the tasks performed on modern computer systems. Rather than adopt these generic devices for task specific problems, researchers are exploring the use of device specific solutions providing a fruitful area of research. Existing devices do not fully exploit the highly dexterous human fingers that are capable of expressing multi-fingered gestures and sensing a wide variety of material feels. Exploring the use of natural affordances to assist in the design of new input devices, intuitive, versatile and high fidelity technologies will emerge.

This chapter has presented the state-of-the-art of input devices and interaction techniques that are that are relevant to this dissertation. There is a significant existing body of knowledge that has supported the direction of research and provided valuable insights into a well established domain. This dissertation addresses some of limitations of the existing approaches and explores new directions that might be considered to further enrich human-computer interactions.

3

Sculpting Metaphor

"Now let me show you my plan for sending you home, please excuse the crudity of this model, I did not have time to build it to scale or paint it!"
Doc. Brown
Back to the Future

"Why Sculpting ?", humans have used their hands for shaping and manipulating physical materials throughout time, from making sand castles at the beach to sculpting clay on a pottery wheel. Computer modelling systems have adopted techniques based on these activities and incorporated them into three-dimensional CAD environments through the use of iconic toolkits. However, currently aspects of computer modelling applications are dissimilar to physically sculpting. Free-form modelling of soft materials is performed using one's hands by pushing, rolling, pinching, adding, subtracting, stretching and flattening the raw material. In comparison computer modelling systems use input devices such as a mouse, SpaceBall™ (3D mouse), tablet, pinch gloves or Phantom [MASS94] to capture gestures performed during computer sculpting. Although these devices capture aspects of the natural sculpting process, further research is required to more accurately capture key operations, such as the interpretation of multi-handed and multi-digit gestures, to more accurately model the naturally engaging sculpting process. This chapter presents my investigations into identifying key aspects of the sculpting process and explores the possibility of incorporating them into the human-computer interaction process.

When sculpting, artists use both soft and hard raw materials, including ivory, clay, stone, granite, metal, glass and wood, and shape these materials into three-dimensional models. This dissertation is concerned with softer material sculpting for two reasons, firstly they can be moulded into an arbitrary shape with bare human hands and secondly this property has enabled most humans to have exposure and some sculpting experience, a valuable affordance that can be leveraged. With this in mind, for the purposes of the sculpting metaphor described, I am concerned with materials such as clay, modelling clay, Play-doh® and the like.

This chapter begins by defining what a metaphor is and describing its relevance in human-computer interaction design. Proceeding this a description of the soft material sculpting process is provided including the identification of significant bare-hand sculpting techniques. Following this, characteristics of the bare-hand sculpting process are described and analysed using HCI design philosophies. An argument for capturing the physical world sculpting techniques and using them for a virtual modelling metaphor is presented based on this analysis. The properties identified are used to formulate a list of characteristics that describes features of a theoretical hardware input device that allows physical world sculpting gestures and techniques to be captured on a computer system. A summary of initial questions that define the problems that are of interest to this dissertation are summarised as follows:

- Philosophical: What are the benefits of capturing physical world sculpting techniques and applying them to virtual modelling?
- Philosophical: Do existing HCI practices and philosophies support the sculpting metaphor?
- Technical: How can multiple finger gestures be captured simultaneously?
- Technical: How can similar clay-like haptic sensations be emulated on a computer input device?
- Techniques: What virtual sculpting techniques can be developed to emulate the existing physical world sculpting techniques?
- Techniques: How can virtual sculpting techniques be extended to support functionality that is not possible in the physical world?

3.1 Metaphors in Human-computer interaction

A metaphor is defined as the presentation of one idea in the terms of another [ALTY99]. They allow a user to have an understanding of how something works based on an common existing concept they are familiar with. The idea of using metaphors for human-computer interaction is a well know technique. The ”Desktop Metaphor” relates the idea of manipulating papers on a physical desktop to the idea of manipulating virtual information, such as icons, on a computing system. Another well known computing metaphor is the ”Windows Metaphor”, where users have views into different applications much like looking through windows in on a building. The purpose of these metaphors is to allow users to more easily interact with a computer system. The idea was first introduced by Alan Kay at Xerox PARC and implemented in the Xerox Star system. Since then metaphors and design methodologies have played significant roles for human-computer interaction design [LAKO80, ALTY99].

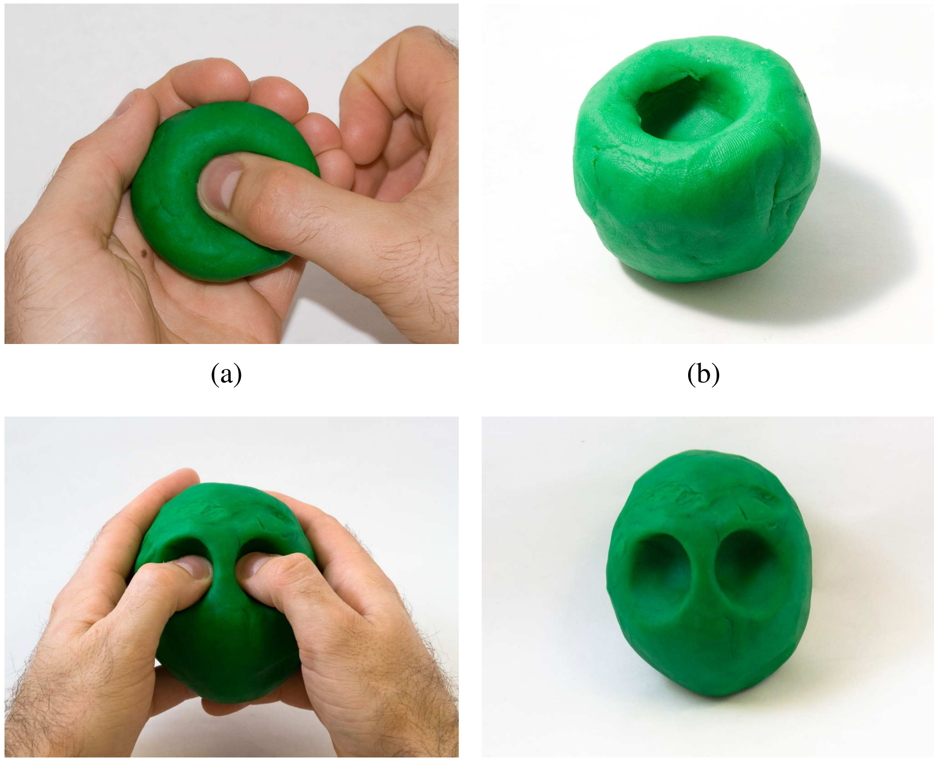
3.2 Material free-form sculpting

Softer materials, such as modelling clay, are pliable and can easily be shaped with bare hands. No fixed techniques are employed for creating clay sculptures, artists develop their own techniques and processes over time. However, there are a number of commonly employed steps beginners study to learn the basic techniques. Often a picture or drawing is prepared and referenced during sculpting. The physical process begins with the raw material being roughly shaped to capture the proportions of the desired model. During this process material can be added "sculpting on" by attaching pieces through forming, water is also used to assist with bonding. Clay is removed "sculpted off" using bare fingers, a potter's knife or other tools. Once the desirable shape is created a technique called detailing is used to add textures and perfect the final design [NIGR92, BOOK05].

The process outlined above discusses a general, high level process utilized to create a soft material sculptures. Sculptors dedicate a great deal of time to develop their techniques and perfect their art form. Most people do not posses the same finely honed skills of the physical sculpting artist. However it is also common for most people to have some exposure to basic sculpting, especially during childhood years. For example Play-doh®, invented by Noah W. McVicker and Joseph S. McVicker [MCVI56], was introduced to school children in 1956. Its soft, pliable consistency and non-toxic physical properties are well suited for hand manipulation, particularly for those with weaker hands. Given these types of exposure, basic sculpting skills are possessed by many humans. Even if no specific sculpting process is known, people are familiar with the feel and understand how soft materials react when manipulated. It is the goal of this dissertation to leverage the existing skills and familiarity with physical world sculpting and capture the techniques so they can be applied to a computer-generated visualisation system.

3.2.1 Techniques

Many techniques and training exercises are used to develop sculpting skills. A common introductory task is the shaping of geometric solids such as spheres, cubes, cylinders and



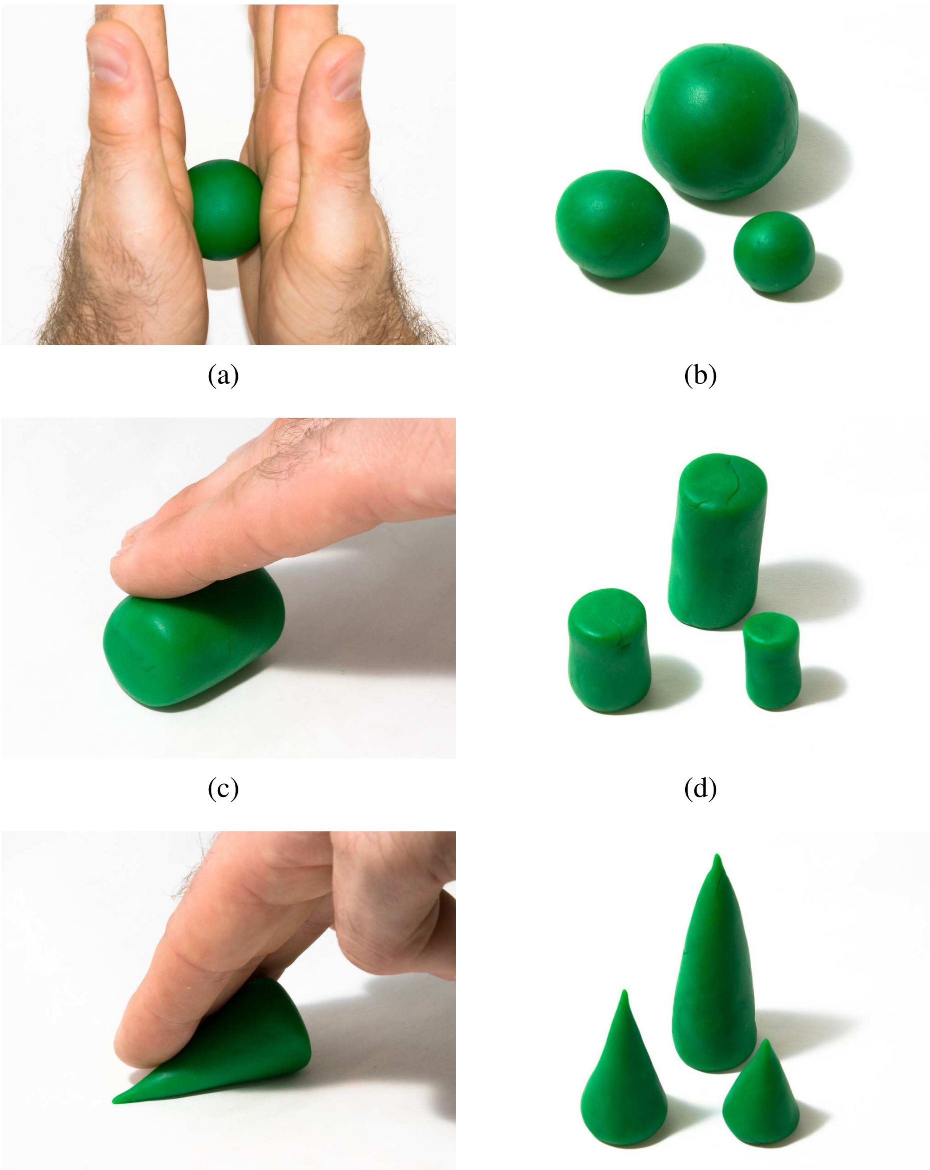
(a) (b) (c) (d)

Figure 3.1: Soft material pushing techniques: (a) Non-dominant hand used to support the material and the dominant hand's thumb used for sculpting. (b) Resulting model with depression. (c) Two thumbs used to create eye sockets in Play-doh®. (d) Resulting model with depressions.

cones. To adopt aspects of the hand gestures for computer modelling, a summary of bare hand sculpting techniques is provided. The following sculpting techniques, pushing, rolling, adding and subtracting are described as basic bare hand free-form operations [NIGR92, BOOK05] and describe desirable multi-fingered bi-manual sculpting operations:

Pushing is performed with one or two hands using a number of different styles. Figure 3.1(a) provides an example using the non-dominant hand to support the material while the dominant hand's thumb presses into the material. The dominant hand's fingers can be used to provide additional support to guide the thumb during shaping (the shaped material is shown in Figure 3.1(b)). An alternate technique is shown in Figure 3.1(c) where the user's fingers of both hands are used to support the material while both thumbs create a depression (The shaped material is shown in Figure 3.1(d)).

Rolling is achieved with one or two hands. Figure 3.2(a) demonstrates the shaping of a sphere using a rolling motion with two cupped palms. Rolling the material against a flat surface is also easily performed, a cylinder is created using rolling and gentle tapping of the ends to shape them correctly (shown in Figure 3.2(c) and Figure 3.2(d)). A cone can be

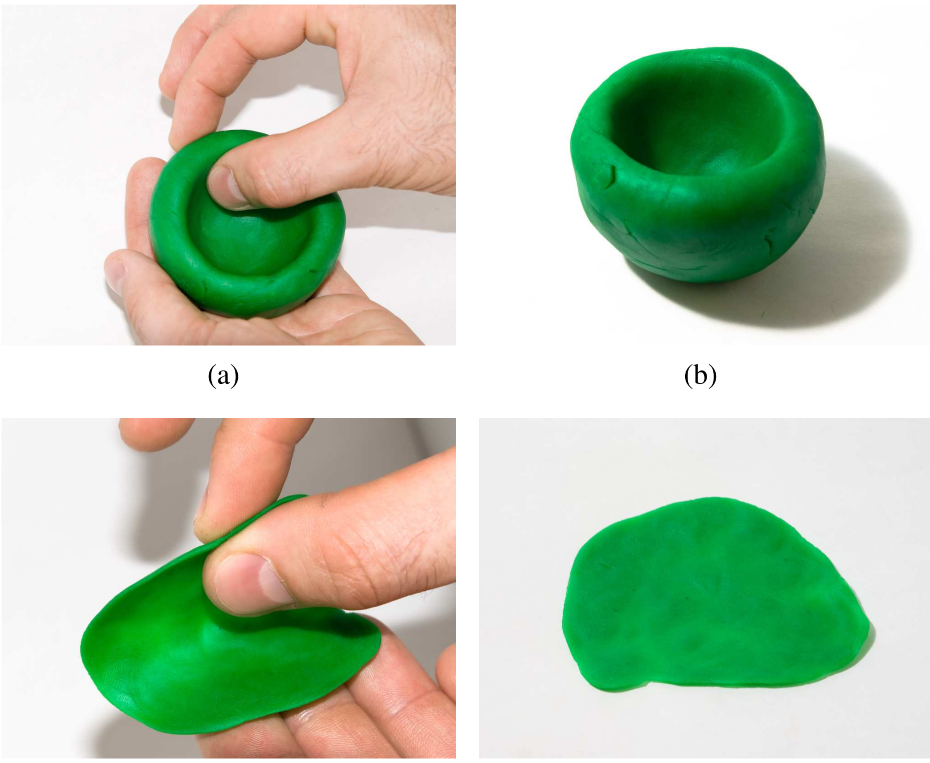


(a) (b) (c) (d) (e) (f)

Figure 3.2: Rolling: (a) Two handed rolling. (b) Hand rolled spheres. (c) One handed rolling using a flat surface. (d) Hand rolled cylinders. (e) One handed rolling with uneven pressure applied. (f) Hand rolled cone.

created by applying more pressure on one side while rolling (example shown in Figure 3.2(e) and Figure 3.2(f)).

Pinching using the thumb and forefinger is another useful shaping technique. A repeated pinching action stretches the material and is performed to create different shapes. In Figure 3.3(a) the user is pinching the sides of a cup shaped form his slowly increasing the size of the cup as shown in Figure 3.3(b). Pinching can also be used to flatten the material to a very thin form, Figure 3.3(c) and Figure 3.3(d) provide an example where the material is pinched to less than 1mm thick.



(a) (b) (c) (d)

Figure 3.3: Soft material pinching techniques: (a) Pinching the edge of a cup using thumb and forefinger. (b) Hand pinched model. (c) Pinching used to flatten material. (d) Very flat material.

Adding during the sculpting process is performed repeatedly to build up areas of a sculpture. A simple form of adding a material is shown in Figure 3.4(a) where simple geometric solids are pushed together to create a humanoid shape. In the second example, a small sphere of material is added to the nose area and formed into the head (show in Figure 3.4(b)).

Subtracting is often performed with a tool such as a palette knife but can also be done using bare hands. Figure 3.5 shows a user supporting the material with the non-dominant hand and removing a small piece of material with their dominant hand.

3.2.2 Discussion

This section has discussed basic soft material sculpting techniques, the purpose is to provide examples of physical world sculpting and consider aspects for the adoption with virtual modelling techniques. The examples presented capture fundamental techniques that in the

(a)

(b)

Figure 3.4: Adding: (a) Geometric solids added together to create humanoid figure. (b) Adding material to the nose of a head.

Figure 3.5: Subtracting material using a pinching and tearing gesture.

physical world are easy to perform and can be achieved with little instruction. However, providing the same expressive functionality on a computer modelling system is currently not possible using existing technologies. It also raises philosophical questions, technical challenges and interaction technique design considerations about how the techniques can be adopted.

3.3 Design philosophies

This section describes a number of HCI design philosophies that support the sculpting metaphor. The aim is to explore physical shaping techniques that can be leveraged to support new virtual modelling interaction techniques. To adopt the physical sculpting techniques described to a virtual environment, the input device functionality needs to support the capture of complex finger gestures performed during sculpting. Using the examples described above, an analysis of the sculpting techniques is performed to support an argument for the adoption of sculpting aspects, such as finger gesture capture and haptic sensations, and describing characteristics of a device that are well suited to capture the sculpting operations described.

3.3.1 Physical sculpting gestures

Cardoz categorises gestures into three groups: semiotic, ergotic and epistemic [CARD94]. Semiotic gestures communicate information, such as a "shrug" indicating not knowing the answer to a question. Ergotic gestures manipulate physical objects, for example sculpting clay. Epistemic gestures are exploratory allowing humans to learn from the environment through tactile experience, for example finding the home keys on a keyboard. In the sculpting examples provided above, both ergotic gestures are used for the shaping of the soft material and epistemic gestures may be used for navigation using known features of a sculpted model.

There are a number of existing design philosophies that justify the capture of physical sculpting gestures. Working with two hands is common amongst many physical world tasks, sculpting is a good example. Hinckley et al. discuss the vital role two-handed interactions play for the interactive manipulation of virtual objects. When working in close proximity to each other, a user's hands provide a perceptual cue or frame-of-reference that is independent from the visual cues and provide information to the user that can not be done with one hand alone [HINC98]. Fine grained finger manipulations for input device design have also been explored by Zhai et al. who suggested that "design affordances of input devices (i.e. shape and size) such that the fingers are included in their operation to whatever extent is feasible" [ZHAI97]. These design philosophies suggest that sculpting is a good example of a physical task that encompasses both bimanual and multiple finger control during operation. By capturing ergotic sculpting gestures and providing appropriate haptics, the expressive nature of physical sculpting can be adopted to support the creation of virtual models. Currently, existing technologies do not fully support the functionalities required to capture the techniques described above, however aspects of existing technologies can be adopted to capture more detail of these gestures. To achieve capturing the complex nature of finger gestures a technology that is not restricted to a single tracked point needs to be employed. A multiple point touch sensitive surface employed for the proposed input device surface would allow the capture of multiple finger interaction points simultaneously.

3.3.2 Affordances

Carefully designing an input device to leverage user's existing skills supports an intuitive understanding of how to operate the device without instruction. Norman suggests that careful industrial design can suggest how the device is used by simply looking at it [NORM88, NORM07]. A benefit of designing a computer input device to capture aspects of the free-form sculpting metaphor is firstly that any physically and mentally capable person can participate, children and adults alike. And secondly, many humans have an understanding and are familiar with a basic sculpting process. In order to suggest how a soft material sculpting input device works is difficult because the distinctive features are technically hard to recreate using existing input device technologies. However, there are design considerations that can be applied. Firstly, using a prop that can easily picked up like a ball of clay will support the operations such as rolling between two hands. Designing the device to be easily manipulated with hands and fingers is also suggested by Zhao et al. [ZHAI97]. A generic shape such as a sphere with a similar size to juggling balls allows easy handling of the device.

3.3.3 Tangible props

Hinckley et al. pioneered a neurosurgical visualization system that employs familiar physical world objects for the design of a three-dimensional user interface [HINC94]. A physical doll's head and flat piece of plastic were used to represent a computed tomography (CT) scan of a 3D skull and cutting plane model (described in detail in Chapter 2). This system captures the user's gestures from the physical world, called the natural dialogue, and applies them to manipulations in a virtual world. The tangible props provide natural passive haptics when grasped and kinaesthetic feedback the perception of the body position, movement and muscular positions. In each of the physical sculpting examples provided above there is a notable similarity between the human interactions of physically sculpting and those of tangible props used for three-dimensional interfaces. Following the design suggestions by Hinckley et al., a task specific prop is desirable and provides an obvious and familiar use with a realistic haptic feedback. Applying this to the sculpting example is difficult because the shape of the malleable material is not fixed. However, a generic shape that is commonly use such as a sphere or cube can be chosen to provide similar functionality. The surface of the device could also be augmented with a deformable material to provide a similar tactile response to soft material sculpting. Materials such as silicon rubber or foam that can be squashed with bare hands allow sculpting-like gestures be performed.

Recently Holman et al. have describe a more advanced tangible device that can take on a new shape or form under computer control. They called this conceptual tangible devices an organic user interfaces (OUI) and describe how a deformable interface can be adapted to support different functionality as required by the desired task [HOLM08]. The idea of allowing the shape of the input device to be modified is well suited to capturing the deformable aspects of physical sculpting and might be leveraged as technologies become available to support these devices.

3.3.4 Tactile response

The feel of an input device provides a great deal of information to the user and needs to be considered for the construction of a sculpting device to provide a similar tactile response. In terms of developing a hand-held sculpting device either active or passive haptics can be employed, each providing different advantages. With active haptic devices the feel is controlled by the computer, with passive devices the mechanical properties of the material determine the tactile response. Using an active haptic device introduces a number of interesting challenges, the Phantom [MASS94] offers a means of tracking a single location in 3D space with active haptics. To operate the Phantom, the user holds a pen like handle to interact with the system, this allows free-form manipulation to be performed using mathematical models to emulate different material properties. Two Phantom devices can also be used side-by-side allowing two handed interactions. Current models of the Phantom also support clip on effectors to capture two finger pinch gestures. However, with the current Phantom aspects of sculpting operations can not be emulated. For example, a user can not use all ten hand digits to deform a virtual object's surface with ten depressions simultaneously. A Phantom does not offer the ability to provide separate active haptics to each finger. Additionally, the working volume is restricted to the volume supported by the mechanical arm of the Phantom.

Cyber Gloves II [IMME08] have 22 join angle sensors that capture complex finger gestures, however since they are worn the user's hands the sens of touch is reduced and interacting with virtual objects there is no haptic sensation. Active haptics have been incorporated with pinch gloves but their bulky nature make them significantly cumbersome. Active haptic pinch gloves, such as CyberGloves support a great deal of the desired functionality, however they are fundamentally dissimilar to the hand-held nature of physical world sculpting examples provided. Computer controlled actuators attached to gloves emulate a physical presence of virtual objects, but there are a number of restrictions, firstly gloves require the donning of large mechanical components that are cumbersome. Secondly, they provide haptic sensation by restricting the movement of digit segments but do not stimulate the finger tips unlike when sculpting soft materials.

Although passive devices do not provide the dynamic flexibility of active haptics, a carefully selected material can improve the perceived realism and transparency of the input device [JUXX03]. Ju et al. performed a study employing deformable materials with force sensitive resistors. As user's pulled on a joystick device, neoprene is compressed, providing an elastic response - the feel of this device was preferred by users over a non-deformable surface [JUXX03]. For a passive hand-held sculpting device, a similar approach might be employed, this can be achieved by covering the surface of the device in a deformable material such as neoprene, silicon, or foam. By using these types of materials, the feel of the device's surface is similar to that of soft sculpting materials like clay or Play-doh®. Pseudo haptics [LECU00] using visual stimulus, might also be used with deformable materials to further immerse the user with realistic material responses.

3.3.5 Spatial reference

The problem of capturing user's finger movements in the real world and translating them into useful information in a computer system is a well researched area [PAIX05, KRYX06]. However, there is limited previous work that has successfully captured complex finger movements to support natural sculpting operations. Most modelling systems restrict user's finger movements to pre-defined axes. Computer applications using these input devices are written to capture this information and translate the simplified input into more complex co-ordinate systems using a number of steps rather than capturing the user's original movements. The advantage of a direct mapping between the user's fingers, input device and 3D model is that users are not required to perform mental spatial mappings to understand the correlation between the device and display [KEIJ07, WIGD06].

Maintaining a spatial reference between an input device and the interactions in a three-dimensional environment can reduce a user's cognitive load [SEAR03]. To achieve this with a fixed shape tangible prop ideally the shape of the input device needs to be the same as the model in the virtual world. Although this is difficult it may be possible with a deformable hybrid material or actuated malleable surface, however this is not the aim of device described so far.

3.3.6 Direct and indirect devices

Indirect devices separate the input and output device, a mouse is an example of an indirect device where the user moves the device on a table's surface and a pointer's position is displayed on a screen. A touch screen installed directly on a screens surface is a direct input device, a user can touch the surface and the pointer will follow their finger. The hand-held sculpting device described so far could be configured to operate in either direct or indirect operating modes. By projecting the virtual object's geometry onto the surface of the hand-held device a direct interaction technology is achieved. One problem with this is that the spherical shape of the device shape and the virtual model will not match exactly.

3.4 Summary

To support the capture of physical sculpting gestures I have propose a number of features for a conceptual new input device. The characteristics have been derived from both existing HCI philosophies and the physical world sculpting examples presented. A summary of the main characteristics of the proposed device is provided:

- Two-handed interactions: Support to allow rolling gestures through the use of a hand-held prop.
- Gesture capture: Interactive surface and rotation tracking.
- Shape: Spherical shape to support spatial reference and rolling gestures.
- Tangible prop: Provides passive haptics.
- Surface material: The feeling of the surface material should be deformable so as it is similar to soft materials like modelling clay.
- Multi-touch point support: Allows for complex multi-fingered and multi-handed gestures used during sculpting to be captured.
- Geometry capture: Can detect any number of fingers that deform its surface.

Based on the observations presented in this chapter, the dissimilarity between physical sculpting and current computer sculpting techniques is largely a result of the capabilities of input device employed. By exploring new functionality in devices including a deformable surface and the capability of capturing multiple finger gestures on this surface aspects of physical sculpting can be further adopted into human-computer interactions.

This chapter has described physical world sculpting techniques and explored how they apply to established human-computer interaction design philosophies. The purpose is to bring the engaging and interactive nature of physical world sculpting to provide an expressive virtual modelling environment using the proposed input device. To achieve this, the proposed device is a sphere shaped prop with a deformable surface that provides appropriate tactile responses while sculpting. The device described is not generic and rather is task-specific for sculpting although further uses will be explored after the technical construction. A significant difference between the proposed device and existing technologies is the interactive surface is does not attach a sensor to each segment of a user's fingers. Instead the surface geometry will be captured independently providing an interactive surface with a tactile response similar to that experienced when performing physical soft material sculpting.

4

Digital Foam Sensor Conceptualisation, Theory and Prototypes

"To invent, you need a good imagination - and a pile of junk."
Thomas A. Edison

A variety of sensors were considered for the design of a new input device to support the clay-like sculpting operations of Chapter 3. During the search, an interesting material was discovered, conductive foam, that potentially would provide the desired functionality. This chapter begins by defining the parameters required of a sensor technology to implement the proposed input device, followed by the details of the search conducted to find a sensor suitable for its construction. Following this, the theory of operation of a conductive foam sensor is described and proceeding this the technical implementation of four separate hardware Digital Foam input device prototypes are presented.

4.1 Sensor requirements and search

A number of specific sensor requirements were identified as desirable for the construction of the proposed input device and were used during the search for applicable sensors. The list of identified requirements is as follows:

- The sensor needs to be deformable to allow press like operations to be performed.
- Can detect its own surface shape (geometry) in real-time, this may be achieved by using many of the same sensors configured in an array.

- Can be used for the construction of a range of different physical shapes including a spherical shaped prop.

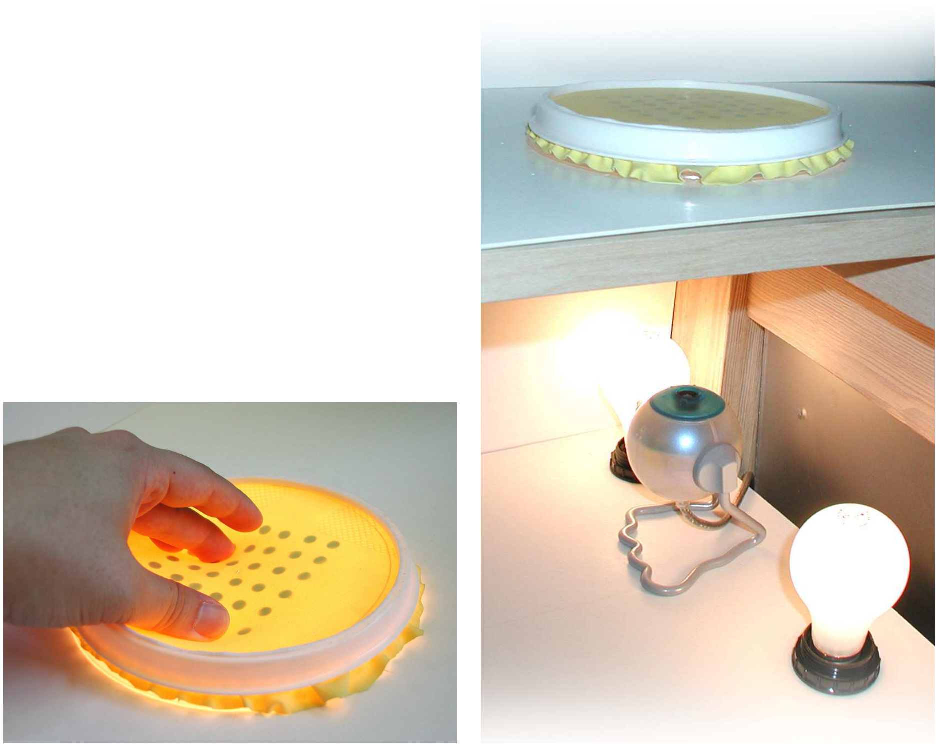
One of the early milestones, after conceptually inventing an input device that can capture sculpting like gestures, was to find a sensor that could be adapted and physically constructed to capture the desired functionality. A number of different sensor types were considered, and possible candidates included: optical based malleable surfaces, arrays of capacitive sensors, linear potentiometers and actuators. Detailed discussions of the example technologies can be found in Chapter 2. This section briefly discusses the sensors considered, identifying the reasons why they were not used in the final design.

4.1.1 Malleable surfaces

Figure 4.1 shows an example of a optically tracked malleable surface [MILC06] developed by Milczynski et. al [MILC06]. The optically tracked malleable surface uses a number of circular markers printed on an elastic material (shown in Figure 4.1(a)) with a camera positioned below (shown in Figure 4.1(b)). When the surface is depressed or manipulated the deformation of the circular markers is used to calculate the surface shape. This sensor meets a number of desirable requirements with a couple limitations. Constructing arbitrarily shaped surfaces is difficult using this technology, for example creating a sphere with the entire surface tracked would be difficult. A number of cameras or a special lens would be needed to view the entire surface. Additionally a support structure, perhaps in the shape of a geodesic dome, is required to hold the silicon taught in an approximate spherical shape. The disadvantage to the support structure is that the tactile response (the feel) of the surface will become inconsistent. For example, as a user runs their finger over the surface it will move over both the unrestricted silicon material and occasionally it will move over the support structure. This non-uniform tactile response is not natural when comparing to soft material such as modelling clay. The use of malleable surfaces is an interesting approach for capturing sculpting operations, however given the limitations outlined I choose to continue searching for alternative sensor options.

4.1.2 Capacitive sensors

Capacitive sensors have been used to construct touch sensitive surfaces. The Tango [PAIX05] is an example of a spherical input device with a touch sensitive surface (shown in Figure 4.2). The Tango captures the location of a user' fingers, however the location of the surface is fixed. So unlike malleable surfaces it is not possible for a user to push their fingers into



(a) (b)

Figure 4.1: Malleable surface input device: (a) Malleable Surface using an elastic membrane material with circular markers to calculate deformations. (b) Camera installed underneath the malleable surface to view deformation information. (Reprinted with permission from Florian Vogt - The University of British Columbia)

the surface. This surface is comparable to a traditional touch surface with the addition that a spherical physical construction is used rather than a planar configuration. One unique aspect of capacitive sensors is that they can detect a proximity without the need for direct touch. However, the fixed surface of these input devices does not allow sculpting operations with a similar tactile response, as defined in the requirements section “the sensor needs to be deformable to capture the desired operations”. Given this restriction it was decided that a capacitive sensor in this configuration is not appropriate for design described.

4.1.3 Potentiometers and actuators

Another possible sensor is the use of resistive potentiometers and actuators for the construction of the proposed input device. Figure 4.3 is a conceptual diagram created to help describe and better understand the physical construction of an actuated input device. In this design a plastic inner skeleton has either linear potentiometers or actuators attached pointing out from the centre of a sphere. A design using potentiometers would capture an approximate

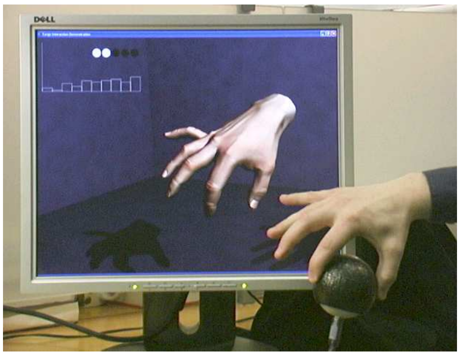


Figure 4.2: Tango, a spherical shaped hand held capacitive input device. (Reprinted with permission from Paul Kry - University of McGill, Montréal)

surface shape by measuring the resistance value to determine the length of each sensor. Using the known position and length of the sensors, a reconstructed geometry can be created. Alternatively, using stepper motors as actuators would not only allow the current length to be measured, but would also allow computer control of the device.

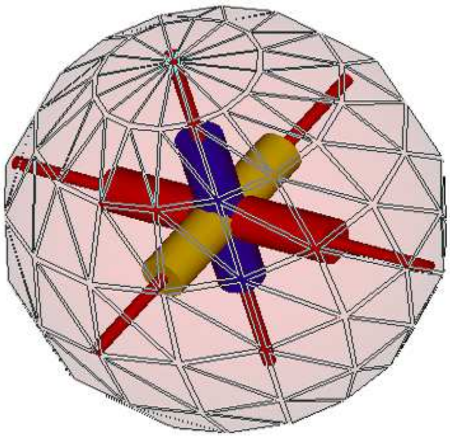


Figure 4.3: Conceptual design idea of an actuated input device. Linear actuators are configured pointing out from the centre of a sphere with a malleable silicon skin used to create the surface material.

To further investigate this approach a prototype was constructed, allowing the tangible device to be physically held, to better understand and visualise how each of the components would fit together. Figure 4.4 shows some of the different components constructed. A custom plastic body was cut out using a CNC milling machine (shown in Figures 4.4(a) and 4.4(f)) with supports for installing a stepper motor. Six of the modules shown in Figure 4.4(c) make up a cube shaped inner skeleton. Additionally, a custom mould was constructed (shown in Figure 4.4(d)), using a CNC milling machine. The mould is used to cast a silicon membrane material (using Smooth On Eco Flex 20) for the outer skin of the prop (Figure 4.4(e)). A white pigment was added to the liquid silicon so that images could be projected onto the surface at a later stage.

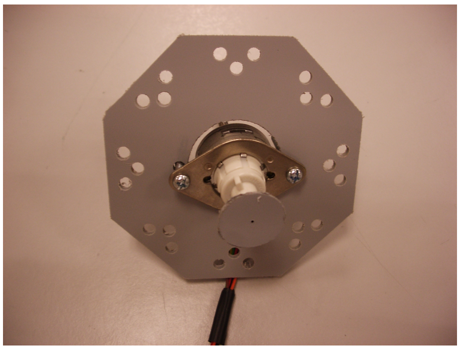
This allowed a number of limitations to be identified, firstly although particularly small stepper motors were selected, the area the motors used inside the plastic skeleton left little room for expansion with only 6 actuators on this prototype. Scaling the design to a different size is also very difficult with out sophisticated manufacturing machinery. Additionally, with the actuators fully extended the prop's outer diameter was 30cm, which is too large to be comfortably used as a hand-held input device. The conceptual idea of an actuated input device is a compelling approach but requires significant miniaturisation of the actuator to provide better resolution. Given these limitations it was decided to continue the search for other appropriate sensors.

4.1.4 Conductive foam

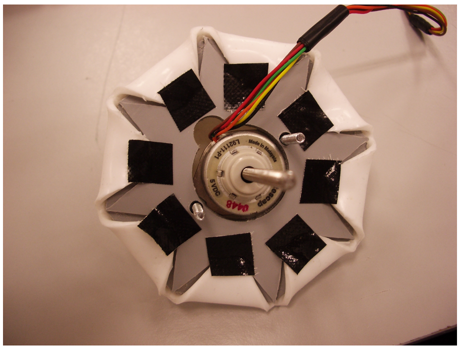
The final approach considered was to use foam, since it would make an excellent medium for an input device designed for sculpting. It allows squeezing operations to be performed and returns to its original shape once released. Integrated circuits are often stored in a special foam that has unique electrical properties, given the unique electrical characteristics it was realised that conductive foam may be used as a sensor. Conductive foam is not commonly used as a sensor, and a short experiment was conducted to test the feasibility. A small sheet of conductive foam was procured and wrapped around a ping ping ball (shown in Figure 4.5(b)) and used conductive tape to terminate the conductive foam (shown in Figure 4.5(a)). A multimeter was then used to observe the resistance change when the surface is squashed (this effect is documented by [BRAD05]). Realizing that a suitable sensor material for the construction of a unique input device may have been found, it was decided that further investigations of conductive foam material was warranted.

4.2 Foam sensor theory of operation

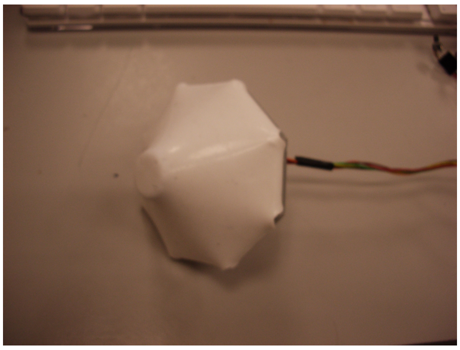
Conductive polyurethane and static dissipative polyethylene foams are traditionally used for storing integrated circuits and providing electrical shielding for noise sensitive electronics. Many varieties are available, with different foam densities, shapes and sizes. Conductive foam can also be used as a resistive sensor similar to a linear potentiometer. The resistance value can be used to determine the current length of the conductive foam [BRAD05] [SMIT08b]. To demonstrate how conductive foam can be used as a resistive sensor a 6mm x 6mm x 1mm piece of conductive foam material was carefully photographed while it was



(a)

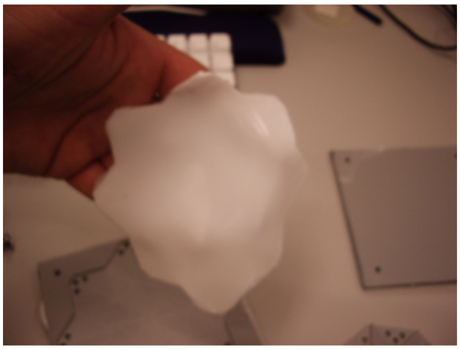


(b)

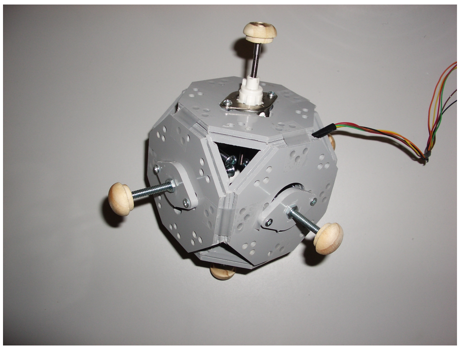


(c)

(d)

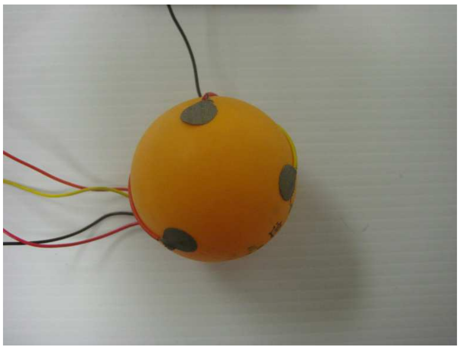


(e)

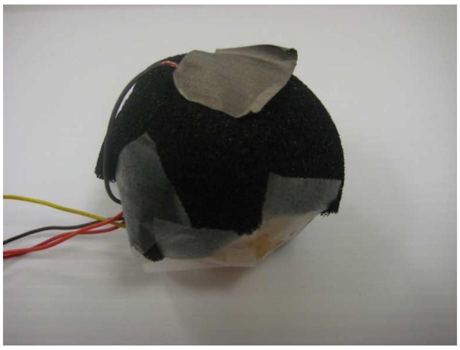


(f)

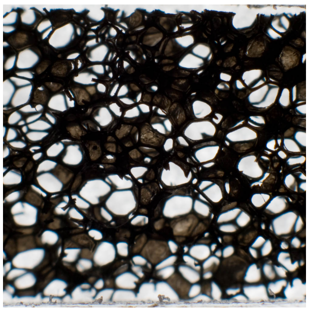
Figure 4.4: Actuated input device prototype construction steps: (a) Single plastic body used to hold stepper motor. (b) Rear/Internal view of a actuated module. (c) Side view of a single complete actuated module. (d) Custom star shaped PVC mould used to cast outer membrane surface. (e) Silicon membrane material removed from mould after curing. (f) Cube shaped plastic skeleton with one stepper motor installed and 5 dummy motors used for visualisation and testing.



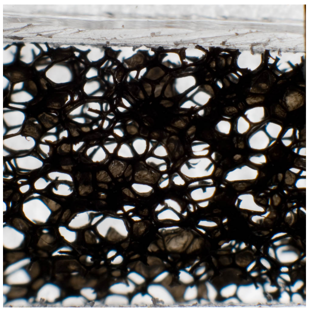
(a)



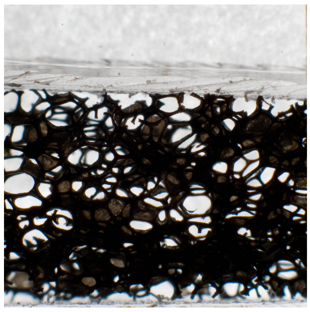
(b)



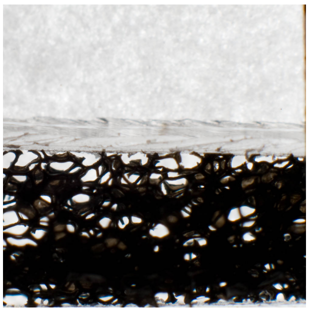
(c)



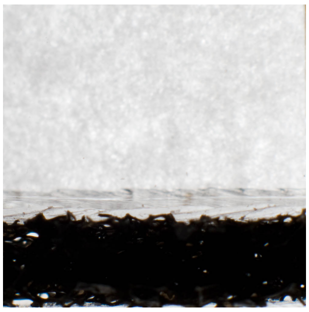
(d)



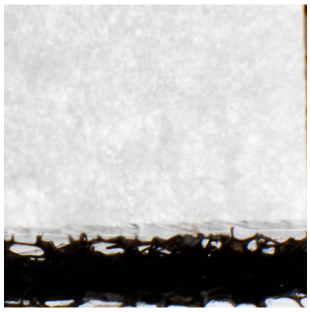
(e)



(f)



(g)



(h)

Figure 4.5: Conductive foam resistance: (a) Conductive tape used as terminals for each side of the conductive foam. (b) Conductive foam wrapped around ping pong ball. (c) Conductive foam with starting width of 6mm. (d) Conductive foam compressed to 5mm. (e) Conductive foam compressed to 4mm. (f) Conductive foam compressed to 3mm. (g) Conductive foam compressed to 2mm. (g) Conductive foam compressed to 1mm.

compressed between two pieces of clear plastic. An external flash was placed underneath the foam to illuminate the foam material making the air pocket visible. Figure 4.5 provides six images that show a 6mm thick piece of low density conductive foam (technical specification provided in Appendix D) that is compressed to be 1mm shorter per image. This highlights the size of the air pockets (sphere shaped bubbles) reducing as the conductive foam is compressed further. This reduces the length of the resistive material and in turn reduces the resistance as it is compressed. This physical property of conductive foam has been used to create an input device sensor allowing a range of new input techniques to be employed.

The experiment presented here was performed to gather some initial resistance values to assist in the design of electronics to measure the resistance value and send the data to a computer. The operation of a single conductive foam sensor used to implement Digital Foam is shown in Figure 4.6. A piece of conductive foam material is carefully terminated on two sides (at opposing ends) to allow a resistance measurement to be taken. An experiment was performed to observe and record the response of the conductive foam material purchased. A multimeter was used to capture resistance values while compressing the foam to different lengths. A 10mm x 10mm x 24mm piece of polyurethane conductive foam was used with copper terminals (10mm x 10mm) to connect the foam to the multi-meter probes. The initial resistance of the 24mm thick piece of foam was measured to be 20k Ohms and when depressed to a thickness of 2mm the resistance changed to 1.5k Ohms. When released the resistance value returned to 20k Ohms.

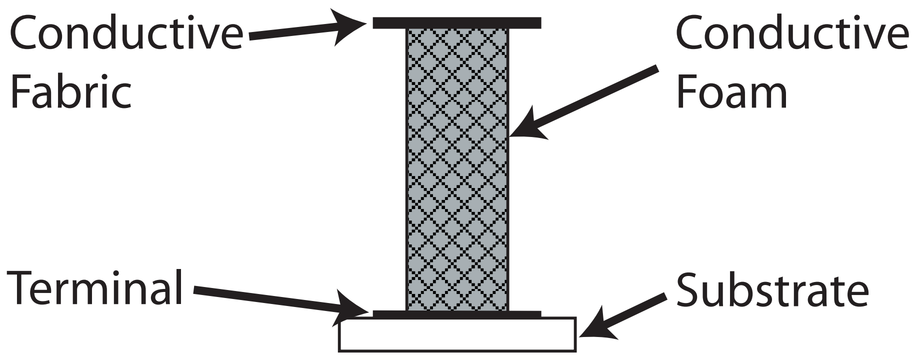


Figure 4.6: Conductive foam sensor theory: A resistive measurement is taken between the conductive fabric and the terminal.

4.3 Prototypes

This section describes the design decisions and implementation details of four Digital Foam prototypes developed. The first two prototypes are based around a planar design and are given the name “Flat Digital Foam”. The later two prototypes are based around a hand-held spherical design and are given the name “Spherical Digital Foam”.

4.3.1 Flat Digital Foam - Version 1

After the promising response of the conductive foam material gathered in the previous test the next step was to design and construct a surface employing an array of analogue-to-digital converters (ADC) with a sheet of conductive foam that would provide an interactive pressure sensitive surface. This sub-section describes the implementation details of the first Flat Digital Foam input device created and the challenges faced during its construction.

4.3.1.1 Physical design

The physical layout of the foam based touch surface using an array of sensors conceptually uses a single sensor duplicated many times. An array of terminals are covered with conductive foam and held in place using conductive fabric, used in intelligent textile designs, that also terminates the top of the foam surface. The first Digital Foam prototype was built using one hundred (10 x 10) foam sensors to produce a 90mm x 90mm working area and a working depth of 20mm. This was chosen to simplify the the construction while at the same time providing sufficient resolution to allow multiple fingers to press the foam surface without overlapping. One hundred terminals were etched onto a printed circuit board (PCB) as shown in Figure 4.7(a).

4.3.1.2 Foam sensors

Before the first prototypes was built it was envisaged that a single piece of conductive foam would be placed directly on top of the terminals. However after initially testing the Flat Digital Foam, using a single piece of conductive foam it was found that the readings of closely located sensors were inaccurate. The reason this occurred is a resistance measurement taken between the terminal and the conductive fabric directly above that terminal is desirable. However, when a single uninsulated conductive foam piece is used, corresponding depressed foam sensors provide a shorter path of resistance and an incorrect reading is measured. To overcome this limitation, a custom piece of foam that combines ordinary non-conductive polyurethane with conductive polyurethane was constructed. Providing an insulating layer between each discrete sensor removes interference of closely located sensors. To construct the customized foam sensor an aluminium die was built and used to cut out an array of one hundred holes in the non-conductive foam (shown in Figure 4.8(a)). Conductive foam inserts are then placed in each of the holes providing an insulated foam sensor array (as shown in Figure 4.8(b)).

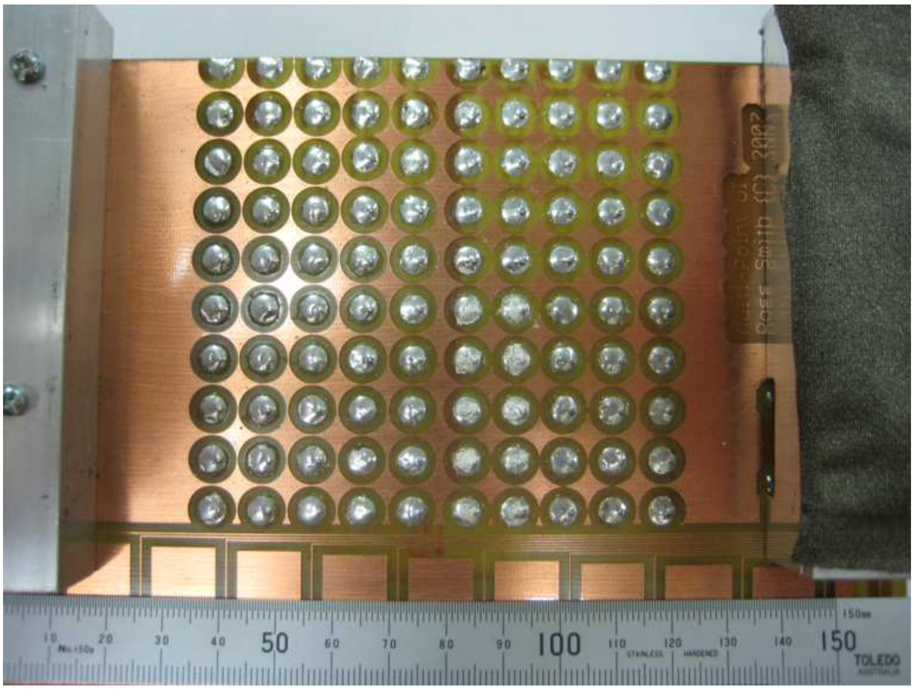
Each of the input device components are then constructed as shown in Figure 4.9. The termination of the conductive foam is extremely important. In order to maintain good termination, a stretchy conductive foam fabric is pulled taught over the conductive foam. The pressure of the stretched material holds the foam sensors in place and maintains good termination on both the top and bottom of the sensor.

4.3.1.3 Foam density

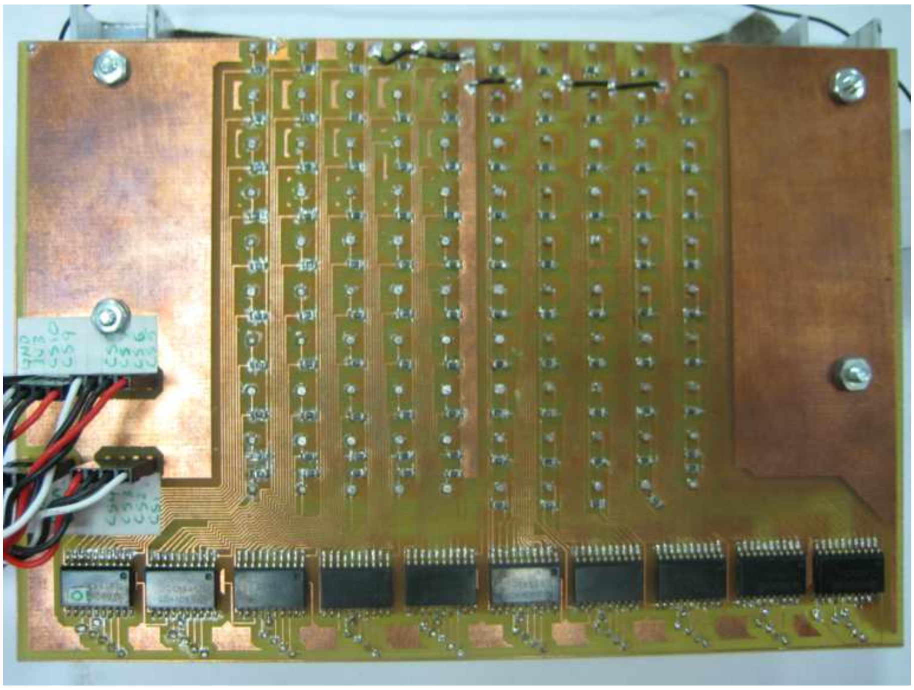
A number of different foam densities were employed during the development of the Digital Foam prototypes. An example of the low density conductive foam selected has a density with a range between 20 and 30 kg/m^3 with a compression hardness of 3.2kPa (+/- 15%). This low density foam is quite soft to touch and can be easily deformed, squashed and twisted with your fingers. An example of a high density conductive foam also available has a density of 46kg/m^3 and a compression strength of 38kPa. The high density foam requires a lot more pressure to deform with your fingers, the goal was to select a foam density that has a similar feel to modelling clay and Play-doh®. Given this requirement the low density conductive foam was selected. Sundin et al. have explored a similar problem, where they compared the effects of "weak elasticity" and "strong elasticity" for input device designs. They compared the performance of the SpaceBall (Strongly elastic) and the SpaceCat (Weekly elastic) devices and found that the elasticity parameter should be considered depending on the task being performed. For example, position control with softly elastic device is better than rate control with a stiffly elastic device [SUND01, SUND09]. The use of the low density foam may influence the position control that is possible and may be altered depending on the desired operations to be performed.

4.3.1.4 Electronics

Each of the terminals is connected to an array of analogue to digital converters on a printed circuit board (as seen in Figure 4.7(b)). Each foam sensor is attached to a single channel of a Texas Instruments 10-bit 11 channel ADC (TLV1543). The ADC provides a value from 0 to 1023 that describes the current length of each foam sensor. Ten separate TLV1543s are utilized to support the 100 input channels required. The ADCs share a common serial bus that is controlled by a Texas Instruments MSP430F1232 microcontroller. The microcontroller is responsible for requesting readings from the ADC chips sequentially and providing a communications interface for the Digital Foam input device. All communications are performed over a Promi ESD class 2 Bluetooth connection. The Digital Foam input device has

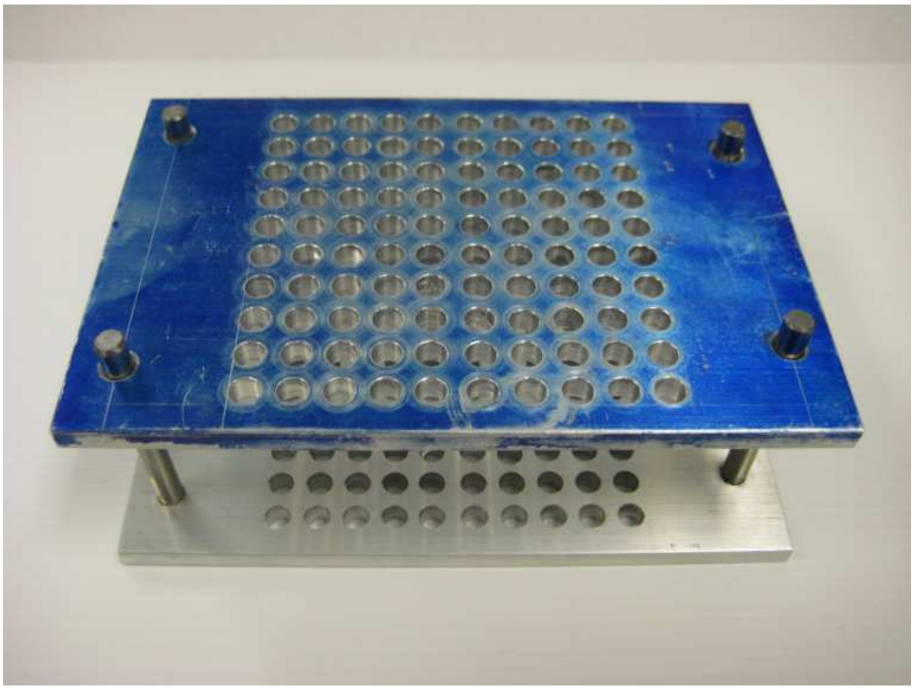


(a)

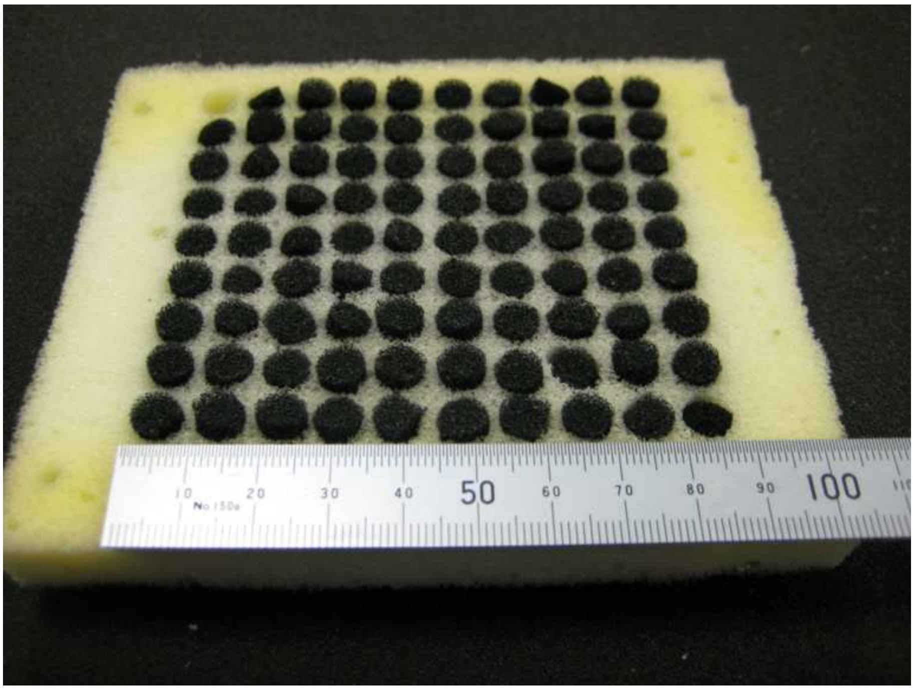


(b)

Figure 4.7: Flat Digital Foam Prototype Construction: (a) Terminal array etched directly onto the circuit board. (b) Ten analogue-to-digital converter chips located on the back side of the circuit board.



(a)



(b)

Figure 4.8: Flat Digital Foam Prototype Construction: (a) Die used to cut one hundred holes in non-conductive polyurethane foam. (b) Conductive foam sensors embedded in non-conductive polyurethane foam.

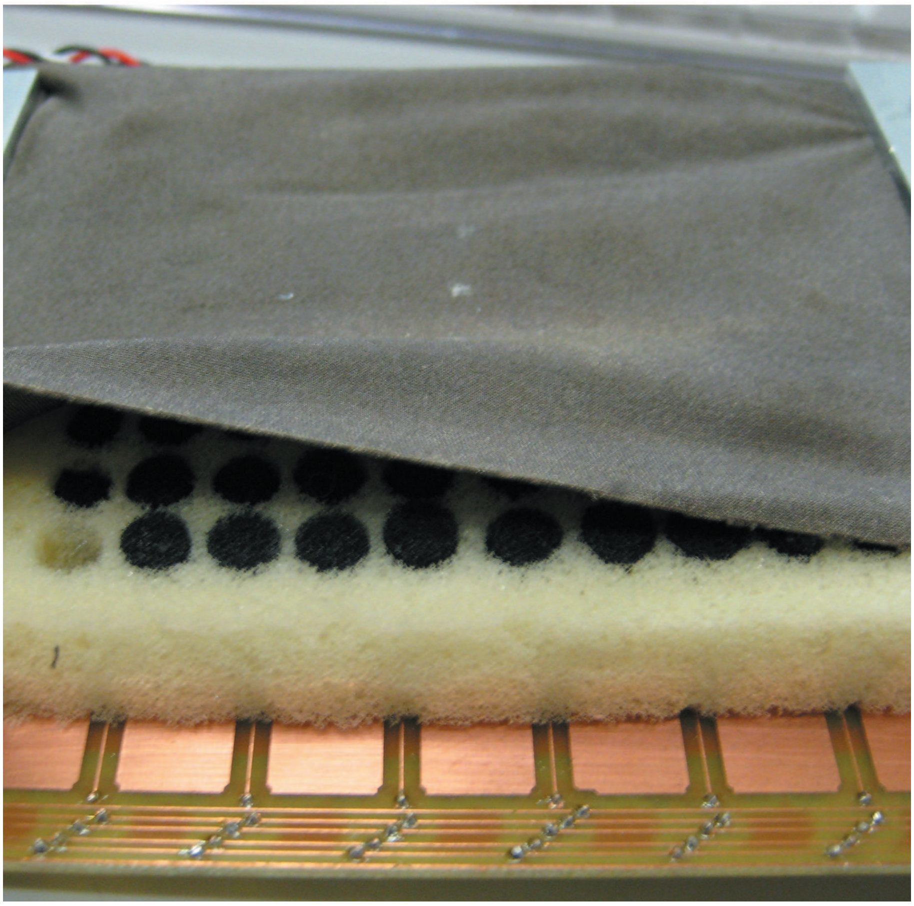
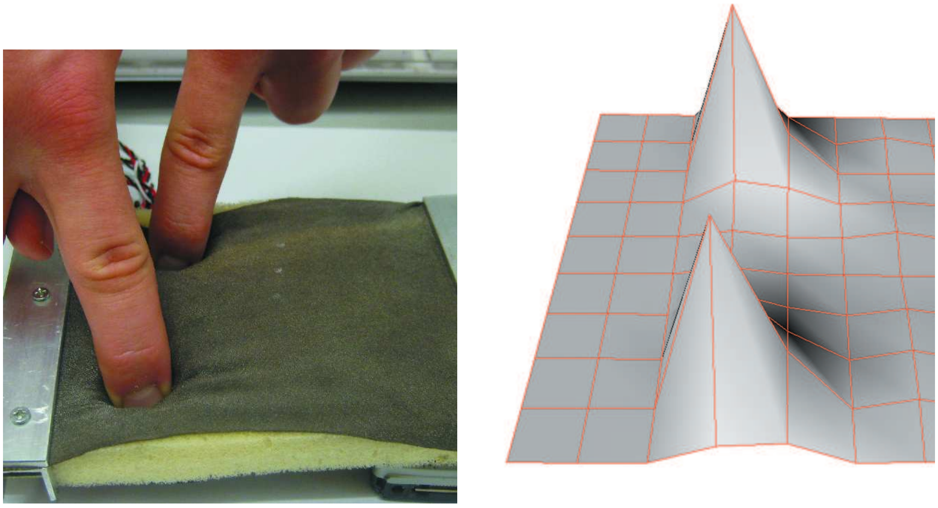


Figure 4.9: Flat Digital Foam with sensor array exposed.

its physical configuration stored on the microcontroller so that when a connection is made, the configuration describing the device's shape, sensor locations, and a tessellation order is provided. Sensor readings are transmitted at 30Hz with a latency of less than 8ms. The schematic used is provided in Appendix B. An alternate design might measure the current rather than a voltage, this could easily be employed but no technical benefits of this approach have been identified.

4.3.1.5 Discussion

The final input device prototypes are show in Figure 4.10(a), where a user is depressing two separate locations with their index fingers. The corresponding geometry (shown in Figure 4.10(b)) is inverted to avoid occlusions in the figure and to verify two finger presses are visible. The working area is large enough to have two users operate the input device with both hands and avoid overlapping in the resulting geometry. The first Flat Digital Foam prototype was very successful in that it provided the first confirmation that conductive foam can be em-



(a) (b)

Figure 4.10: Flat Digital Foam prototype version one: (a) User pressing two separate locations on Digital Foam. (b) Inverted geometry with two finger presses in Digital Foam.

ployed to create a deformable surface capable of capturing it's own geometry. This prototype confirmed the feasibility of the design and that further research is merited. In conjunction with developing new interaction techniques, the next direction would be to construct a more robust Flat Digital Foam design that would physically withstand repeated testing procedures. Finally, concealing exposed wires and electronics to provide a self-contained design is also desirable.

4.3.2 Flat Digital Foam - Version 2

The purpose of a second Flat Digital Foam prototype is to build a robust device that can be used as an interactive table-top surface or as a portable desktop tablet. After the successful creation of the first Flat Digital Foam prototype, design alterations and areas for improvement were identified. Firstly, to conduct a performance evaluation and to be used daily, a more robust prototype is needed to withstand large numbers of repeated stroke like operations. With this in mind, careful attention was focused on the physical construction quality, with particular attention given to the design of the fabric support. Additionally, introducing the ability for projected information on the Digital Foam surface is also desirable. To achieve this, a modification to the existing grey surface colour of conductive fabric material to change it to a white surface colour is required. Finally, "debris tolerance" where small items, such as a marebel, left sitting on the surface cause unwanted sensing have also been considered.

4.3.2.1 Physical design

It was decided that a 200mm x 200mm x 12mm working area, slightly larger than the previous prototype, would allow for sufficient performance testing and allow two users to touch separate locations on the interactive surface. Given that each ADC supports 11 channels, a choice to use an 11 x 11 grid with 11 ADC chips was chosen. This layout simplified the routing of the printed circuit board. The electronics used are similar to the first prototype, with an additional ADC integrated circuit added to support the increased number of foam sensors (previously 100, increased to 121). The circuit board was cut out on a T-Tech[1] PCB mill, and is shown in Figure 4.11(a). Located on the left side of the circuit board is the micro controller, ADCs and supporting integrated circuits. On the right side the terminal array is cut directly into the circuit board (shown in Figure 4.11(b)).

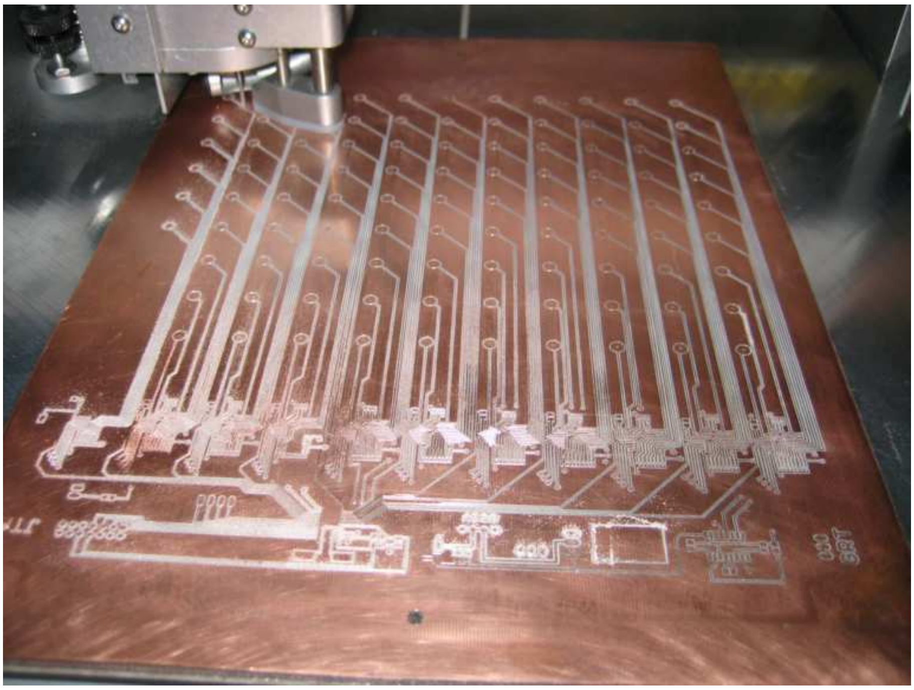
4.3.2.2 Fabric design

As previously discussed, maintaining good termination on each side of the conductive foam is required to reduce data noise and maintain satisfactory operation. The stretchy conductive fabric is used to hold the foam tightly in place without significantly squashing it. To improve the reliability a square plastic frame (Figure 4.12(a)) was constructed in which the conductive fabric is attached securely. A white stretchy (80%cotton and 20%elastin) material was also used to cover the foam surface and allow projected images (shown in Figure 4.14(a)). This material was chosen to allow vibrant images to be projected on the Digital Foam surface while still being able to perform strokes and gesture operations. Using non-elastic fabrics restricts the ability to push into the foam surface and are avoided accordingly. A Mitsubishi PK20 LED projector is installed above the Flat Digital Foam to provide a display surface whilst keeping the setup size small and portable. The projected Flat Digital Foam environment is shown in Figure 4.14(b) and a close up of a projected image can be seen in Figure 4.14(c).

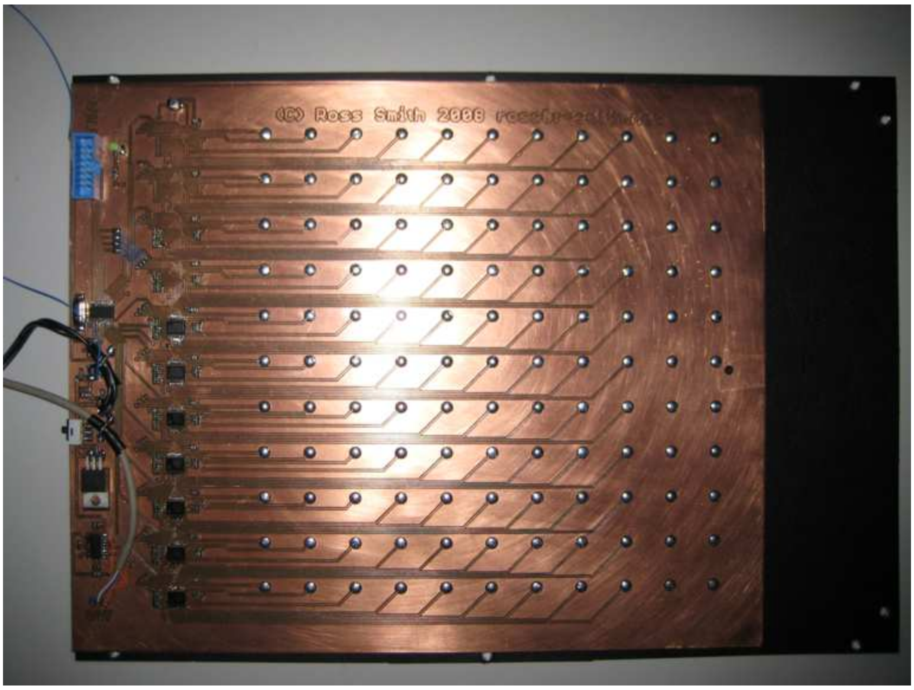
4.3.2.3 Debris tolerance

To further improve the performance a thin sheet of insulating plastic is installed between the terminal array and the conductive foam, with holes cut and aligned with the foam sensor terminals. The plastic sheet creates a mechanical switch isolating the conductive foam from the terminal when no pressure is applied to the surface (as depicted in Figure 4.13(a)). When a small amount of pressure is applied the foam sensor makes contact with the terminal completing the circuit (as depicted in Figure 4.13(b)). The purpose of this switch is to firstly

[1] http://www.t-tech.com/



(a)



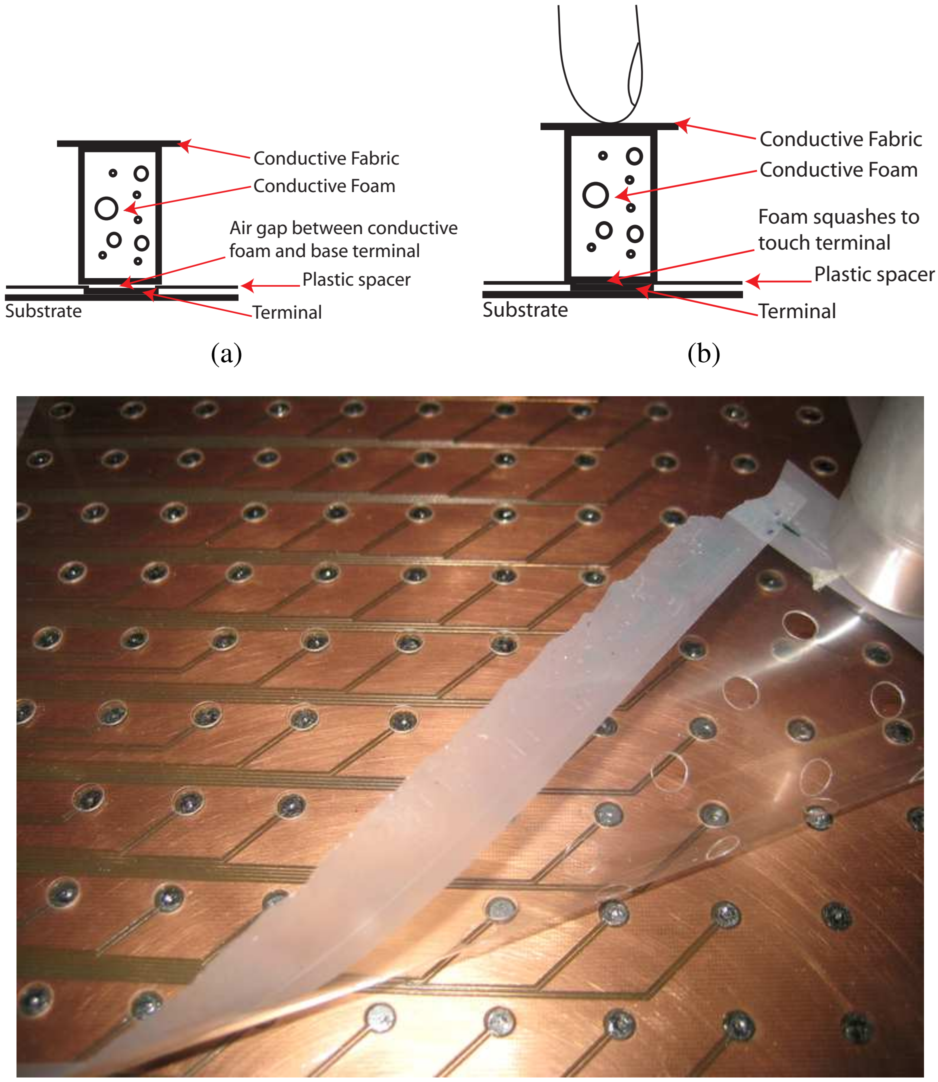
(b)

Figure 4.11: Flat Digital Foam version two construction: (a) Partially milled circuit board using T-Tech machine. (b) Integrated circuits and components mounted on the left side and terminal array on the right side.

(a)

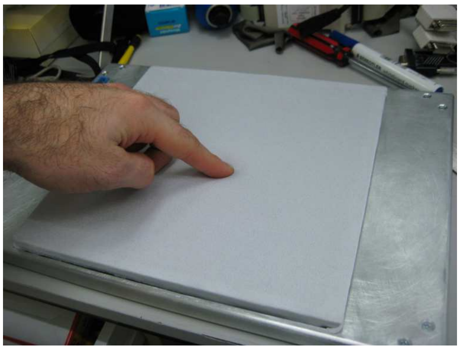
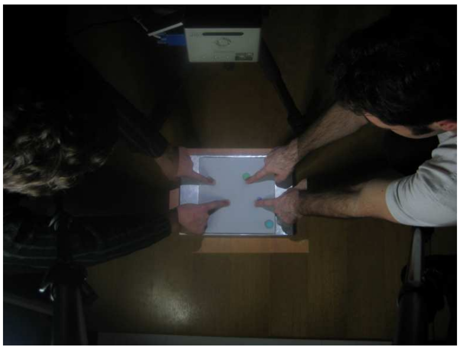
(b)

Figure 4.12: Flat Digital Foam version two construction: (a) Plastic frame used to hold fabric taught. (b) Conductive fabric attached to plastic frame.

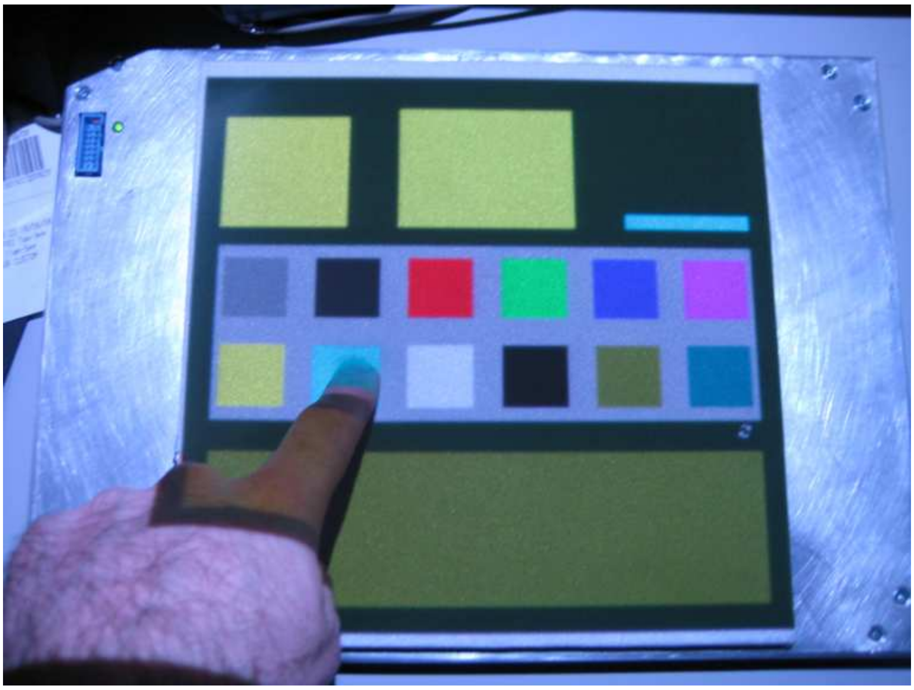


(c)

Figure 4.13: Flat Digital Foam version two. Debris tolerance construction and design details: (a) Operation of the thin plastic sheet used as a mechanical switch in the off position. (b) When depressed, the foam deforms causing it to make contact with the terminal completing the circuit. (c) Thin plastic sheet used as a mechanical switch to improve debris tolerance and noise reduction.

(a) (b)



(c)

Figure 4.14: Flat Digital Foam prototype version two: (a) White fabric installed to create a projection surface. (b) Two users interacting with the projected Digital Foam surface. (c) Close up view of the projected Flat Digital Foam surface.

produce a clean digital signal when the device is in an idle state (i.e. nothing is touching the surface). Secondly, it allows small light-weight items to be placed on the surface without activating the sensors. This plastic barrier could easily be omitted during construction if this functionality is not required.

4.3.2.4 Discussion

The construction of the second Flat Digital Foam prototype has incorporated the design changes identified during the development of the first prototype. A number of challenges including debris tolerance, digital noise reduction and robust performance issues have been considered. This prototype is used extensively for the development of interaction techniques, algorithms, and performance evaluations as presented in the following chapters.

4.3.3 Spherical Digital Foam - Version 1

This section describes the construction of the first of two Spherical Digital Foam input devices created to explore sculpting like interaction techniques that are not possible on traditional input devices. The first two prototypes were constructed using a flat surface, this was done for the proof of concept of the Digital Foam sensor and is now extended to more closely capture the functionality described in Chapter 3. Of particular interest is the creation, capture and modification of 3D geometries. One technique used for 3D geometry creation and capture is to start with a base shape on which carving and other operations are performed to generate a sculpted solid. To intuitively support this type of operation using Digital Foam, a hand-held sphere covered with the Digital Foam sensor has been constructed. The reason a sphere was chosen is to leverage the shape of the physical device using it as a spatial reference in the virtual world. For example, if a user would like to interact with the rear side of a virtual 3D model, touching the back surface of the Spherical Digital Foam will navigate to or manipulate the same location (perhaps with a scale factor) in the virtual world. To support this functionality an orientation sensor was also included as part of the Spherical Digital Foam design.

The construction of a spherical prop with a Digital Foam outer sensor array is more difficult compared to the Flat Digital Foam. Conceptually, to construct the self-contained sphere an inner skeleton containing the electronics, batteries and other components is required. Also to optimise the usability of the design, wires tethering the device are avoided by employing wireless communications.

4.3.3.1 Physical design

The design has an inner skeletal plastic sphere (Figure 4.15(a)) used as a support structure for the outer foam layer. The outer surface of the plastic sphere has evenly spaced terminals, each of which is used as a discrete input for foam sensors. To find the location of the 21 terminals a software repelling algorithm was used; terminal locations are placed randomly on the sphere's surface and magnetically repelled from its neighbours until a steady state is achieved. This approach finds only approximately evenly spaced terminal locations, however its accuracy exceeds what is possible with the mechanical construction used to construct this prototype.

4.3.3.2 Foam sensors and fabric design

Once the location of the terminals was calculated and the metal terminals installed on the plastic sphere, the foam sensors are installed. Similar to the Flat Digital Foam design, non-conductive foam is used to provide both a support structure and electrical isolation so that corresponding sensors do not give false readings. With the limited area of the inner plastic skeleton, the number of sensors was reduced to 21 to simplify the electronics so they would fit.

The foam sensors attached to the sphere are depicted in Figure 4.15(b). A sphere shaped conductive fabric sock was also constructed to terminate each of the foam sensors. One problem faced using this design is the conductive fabric is connected to a ground signal, creating a Faraday cage that blocks wireless signals. To overcome this problem it was necessary to put regular spaced holes in the conductive fabric to allow a 2.4 GHz Bluetooth signal to transmit the sensor data. The final input prop with conductive fabric outer is shown in Figure 4.15(c).

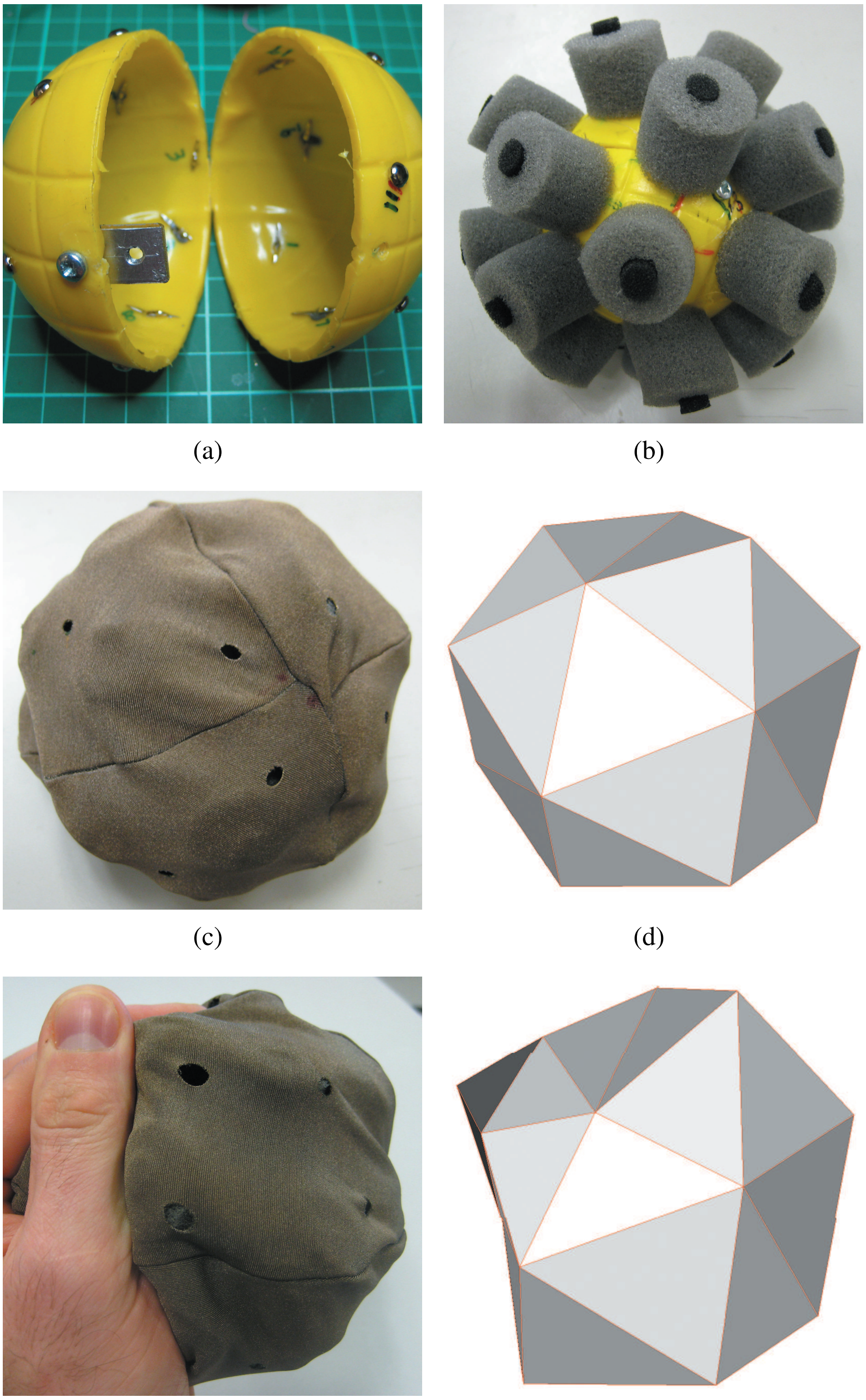
4.3.3.3 Electronics

The electronics are similar to the previous two prototypes constructed, with an additional InterSense InertiaCube 2[2] added to track orientation. A Promi ESD02 Bluetooth wireless transmitter is employed to transmit serial data for the Inertia Cube 2 over a wireless link. A number of step-up regulators (TPS61040 and TPS76133) are also required to increase the 3.7V provided by the Lithium Polymer battery to 6V for the Inertia Cube and 5V for the wireless transmitters and other electronics. This was chosen rather than using two lithium cells due to the limited space inside the plastic skeleton.

4.3.3.4 Discussion

An example of the completed Spherical Digital Foam input device is shown in Figure 4.15(c). The locations and current lengths of each sensor are used to create a virtual model shown in Figure 4.15(d). Each of the foam sensor lengths are updated in real-time to capture deformations that occur on the surface of the spherical device. In Figure 4.15(e), a user is grasping the left side of the input device and the resulting deformed geometry is show in

[2] http://www.intersense.com/



(a) (b) (c) (d) (e) (f)

Figure 4.15: Spherical Digital Foam prototype version one: (a) Plastic inner skeleton with sensor terminals. (b) Foam sensors attached to spherical prop. (c) Spherical prop with conductive fabric outer in place. (d) Geometry representation of sphere prop. (e) User squeezing part of the prop. (f) Geometry captured while user is squeezing the prop.

Figure 4.15(f). This prototype was developed to facilitate the capture of sculpting gestures in a novel manner with the features described in Chapter 2.

4.3.4 Spherical Digital Foam - Version 2

To support a 3D modelling system using Spherical Digital Foam, it was recognized the density of the sensors relates determines the final resolution of the models that can be sculpted. The first Spherical Digital Foam prototype constructed has 21 foam sensors, which was adequate for testing and creating many of the new interaction techniques. However, changing the electromechanical design to iteratively increase the resolution and performance is desirable. By increasing the resolution, the device becomes capable of detecting more detail of the gestures the user is performing giving them more control over during use. A number of new features have been incorporated to increase the hardware performance, these were based on what was learned from the previous experimental prototypes and directed develop of the final Spherical Digital Foam design presented.

4.3.4.1 Physical design considerations

Constructing a higher resolution prototype required difficult technical challenges to be overcome. In the previous prototype each foam sensor was manually attached to the plastic skeleton, a tedious error prone process that does not scale and should be avoided. To improve the scalability, in the next prototype it was decided to create two foam half spheres with all the sensors incorporated into these foam pieces. To achieve this, a new construction technique that combines both the conductive foam and non-conductive foam was required. Secondly, with the increased number of foam sensors, the size of the electronics increases but still must be installed in a confined location and requires very careful design and construction to accommodate the dense electronics. Finally on the 21 sensor Spherical Digital Foam prototype, a set of small holes were cut in the outer conductive fabric layer to allow Bluetooth signals to be transmitted. Although this worked, it was found that when holding the input device with two hands many of the holes would become covered and the signal was attenuated causing slower update rates.

4.3.4.2 Sensor layout

The position of the sensors has to be placed evenly around the sphere's surface to provide a consistent resolution during interactions. To achieve this, a subdivision algorithm [WOO98] was used, rather than the previously described repelling algorithm. The subdivision algorithm generates perfectly evenly spaced vertices on the surface of a sphere, however only certain numbers of vertices are possible. The algorithm starts with one of the five platonic solids and is reduced by dividing each face into four new faces until the desired complexity is reached. By choosing different base platonic solids and performing different division levels there are a large number of evenly-spaced vertices that can be generated. An icosahedron (20 faces, 12 vertices and 30 edges) was selected as the base shape, and 2 levels of subdivision was performed, so the final design has 320 faces, 162 vertices and 480 edges. Table 4.1 provides a summary of the different spacing possible using the first five levels of subdivision on each platonic solid, this table is provided to give an idea of how the number of vertices increases at each level of subdivision. In a practical sense of constructing devices with more sensors, the level of subdivision may be increased accordingly. The sensor layout used for the second version of the Spherical Digital Foam prototype is shown in Figure 4.16.

Tetrahedron			Hexahedron			Octahedron			Dodecahedron			Icosahedron		
F	E	V	F	E	V	F	E	V	F	E	V	F	E	V
4	6	4	6	12	8	8	12	6	12	30	20	20	30	12
16	24	10	24	42	18	32	48	20	48	96	42	80	120	42
64	96	40	96	156	66	128	192	80	192	336	144	320	480	162
256	384	160	384	600	252	512	768	320	768	1248	528	1280	1920	642
1024	1536	640	1536	2352	984	2048	3072	1280	3072	4800	2016	5120	7680	2562

Table 4.1: Platonic solid properties showing next subdivision level each row. F = Faces, E = Edges and V = Vertices

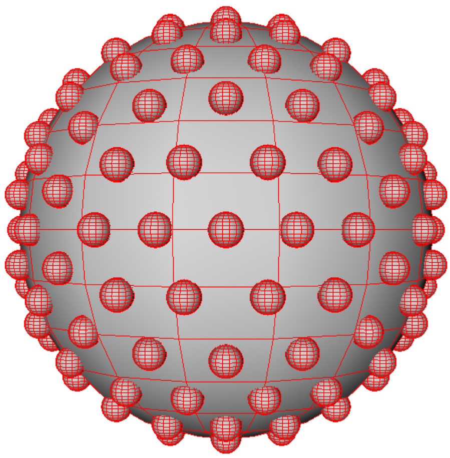


Figure 4.16: Layout of 162 evenly spaced sensors on the sphere's surface generated using a subdivision algorithm [WOO98].

4.3.4.3 Foam sensors and terminals

Insulating the individual foam sensors and maintaining good contact at the termination points is critical to the performance of each sensor. Previously, each sensor was created separately and then attached to the plastic sphere. This approach is tedious and not scalable as the number of sensors increases. To overcome this problem, a technique that employs liquid foam poured into a custom mould (as shown in Figure 4.17(b)) was developed.

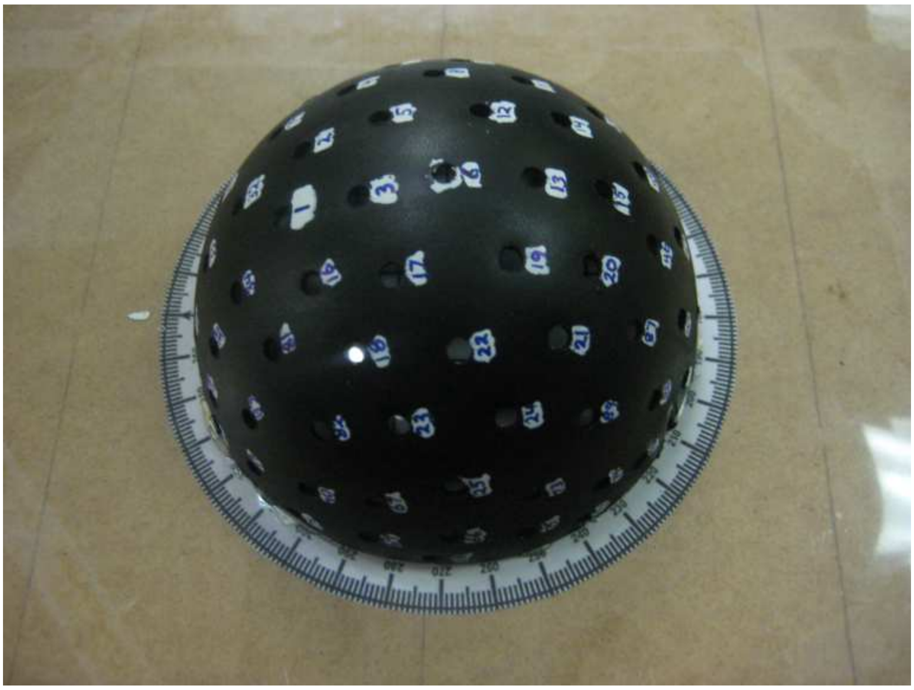
To construct the mould, the vertices generated using the sub division algorithm are transposed onto the inner and outer half spheres that make up the mould. While a 5 DOF milling machine could automate this task, this is highly specialized equipment and was not available, so a manual jig was constructed to perform the transposition manually (shown in Figure 4.19). The manual jig has the advantage of operating in polar coordinates, allowing one data set to be used to mark up any size sphere. The vertices generated from the subdivision algorithm are converted from cartesian coordinates to polar coordinates using the well known Equation 4.1.

$$\begin{aligned} r &= \sqrt{x^2+y^2} \\ \theta &= 2\arctan\left(\frac{y}{x+r}\right) \end{aligned} \tag{4.1}$$

Once marked up, holes were drilled and a 100 millimeter long by 4.5 millimeter thick nail was put into the matching holes of the inner and outer half spheres to create the mould shown in Figure 4.17(b). The purpose of the nails is to create a series of cylinder shaped holes in the non-conductive foam that will have conductive foam inserts placed in each. Once the mould was prepared with a release agent, Smooth On's FlexFoam-iT! III[3] liquid foam was poured into the mould to create the insulating and structural part of the foam sensor as shown in Figure 4.18(a). Once the moulding process is completed, individual conducting foam inserts are placed into each of the holes (Figure 4.18(b)). The insulating part of the sphere's foam surface is built in two halves to simplify the construction, and to allow assembly and disassembly of the final input device.

The same mould was also used to create another customised tool allowing the terminals to be accurately positioned on the inner plastic skeleton. Smooth On's "Smooth Cast 305" liquid plastic was poured into the mould, cured and removed to create the tool shown in Figure 4.19(b). The plastic skeleton is then placed inside the jig and each hole is drilled manually (Figure 4.19(a)). Metal terminals are placed in each hole and securely crimped to the plastic skeleton (shown in Figure 4.20(a)).

[3] http://www.smooth-on.com/

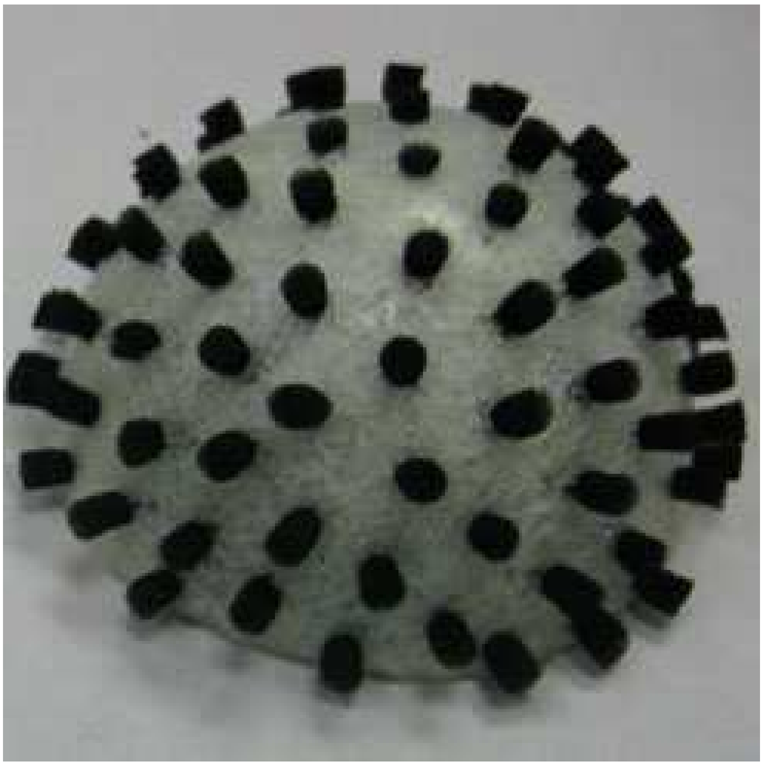


(a)

(b)

Figure 4.17: Spherical Digital Foam construction tools: (a) Jig constructed to mark up plastic half sphere using polar coordinates. (b) Custom mould used for casting foam.

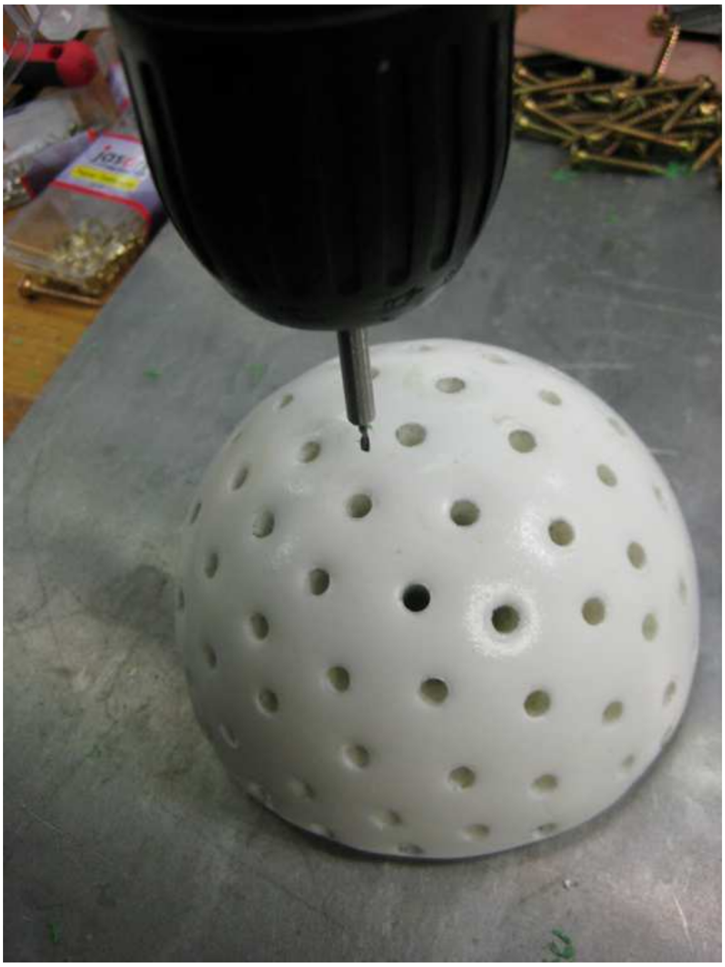
(a)



(b)

Figure 4.18: Spherical Digital Foam custom foam: (a) Custom cast foam. (b) Conductive foam inserts inserted into foam mold.

(a)



(b)

Figure 4.19: Spherical Digital Foam terminal drilling tool: (a) Underside view showing the green plastic skeleton installed inside the white drilling jig. (b) Drill is inserted from the outside through the jig providing support during drilling.

4.3.4.4 Electronics

The electronics used in the 162 sensor Spherical Digital Foam prop are similar in design to the schematics used in the 21 sensor Spherical Digital Foam prop. Additional ADCs were added to measure the resistance of the increased number of sensors. In total, there are 16 TLV1543s, each with 11 channels that allow the capture of the 162 foam sensors. Separate boards were created for each ADC chip and attached to the inner surface of the plastic skeleton; this was done to optimize space usage within the sphere. Each ADC chip is connected to a common serial data bus that is managed with a MSP430F1232 microcontroller[4].

Wireless communications to the microcontroller is performed using a Parani-ESD210[5] Bluetooth module. This module was chosen in place of the Promi ESD02 because of the external antenna. An external antenna was used to improve the signal strength and now protrudes though the conductive fabric outer (Figure 4.20(b)). Unlike the first Spherical Digital Foam prototype, the signal loss is no longer a problem using the new design. The antenna location also doubles as a reference orientation marker so the top location of the device can be easily identified. A 600 mAh Lithium-ion battery provides approximately 6 hours of use before charging is required. Finally, the Inertia Cube 2 was upgraded to a smaller Inertia Cube 3[6] allowing additional room inside the plastic sphere to accommodate the dense electronics shown in Figures 4.21(a), 4.21(b), 4.22(a) and 4.22(b).

4.3.4.5 Discussion

This subsection has presented the second iteration of the Spherical Digital Foam input device. The techniques presented have addressed scalability issues of the physical construction for higher resolution foam sensor devices. This device has further supported the development of the techniques and evaluation presented in the following chapters.

4.4 Summary

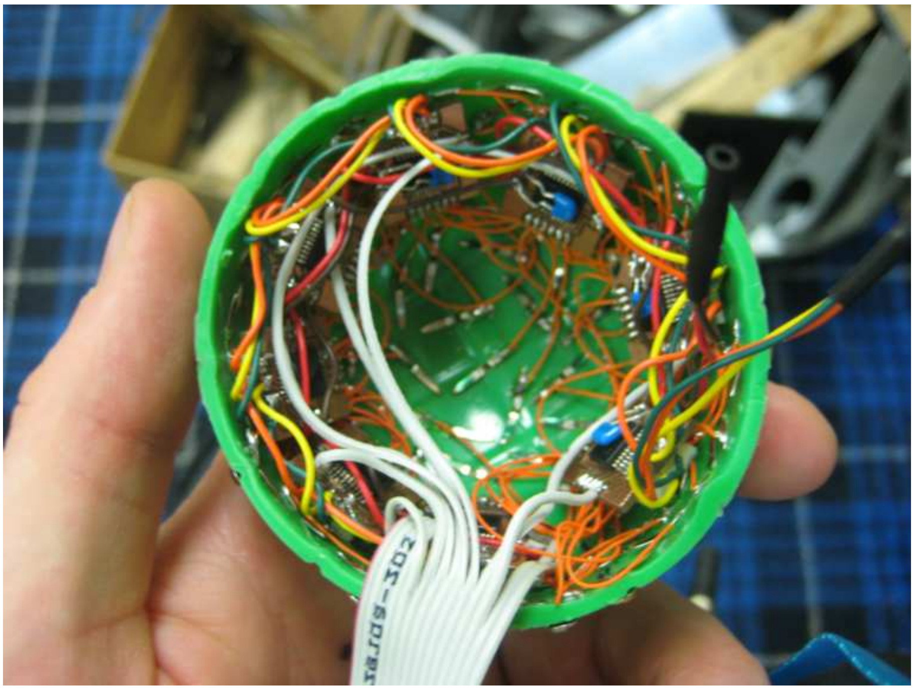
A number of observations were made while developing and working with the Digital Foam prototypes that are presented in a general discussion here. The haptic response of Digital Foam depends on the foam type used. The density of the foam determines how malleable the surface is and in turn how far it can be depressed. Additionally, a unique property of conductive foam is that the return rate after a depression varies significantly depending on the

[4]http://www.ti.com/
[5]http://www.sena.com/
[6]http://www.intersense.com/

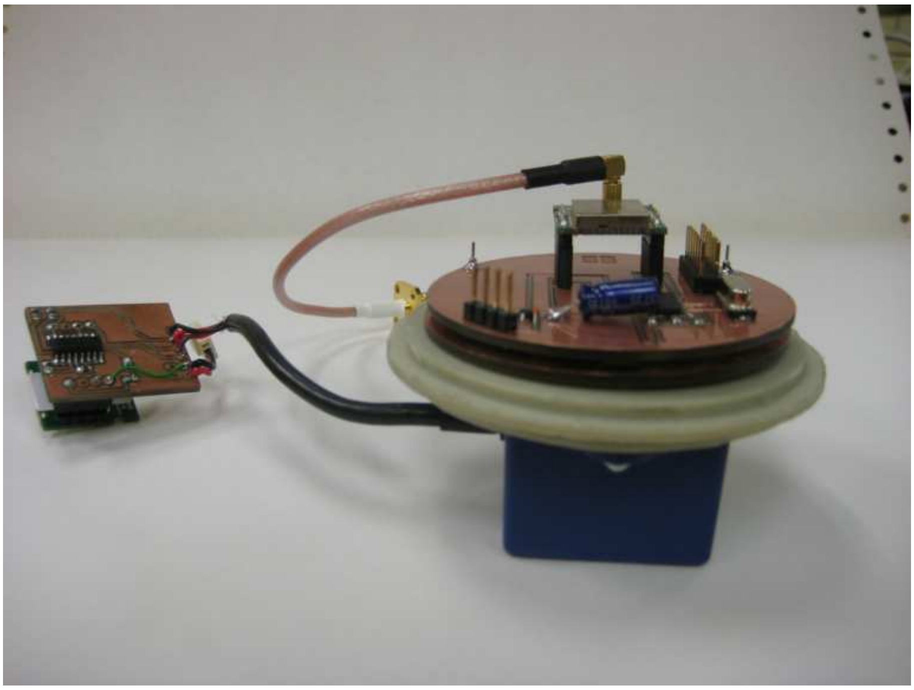
(a)

(b)

Figure 4.20: Spherical Digital Foam prototype version two: (a) Complete electronics with exposed terminals, on/off switch, antenna and charging port. (b) Constructed Spherical Digital Foam input device.



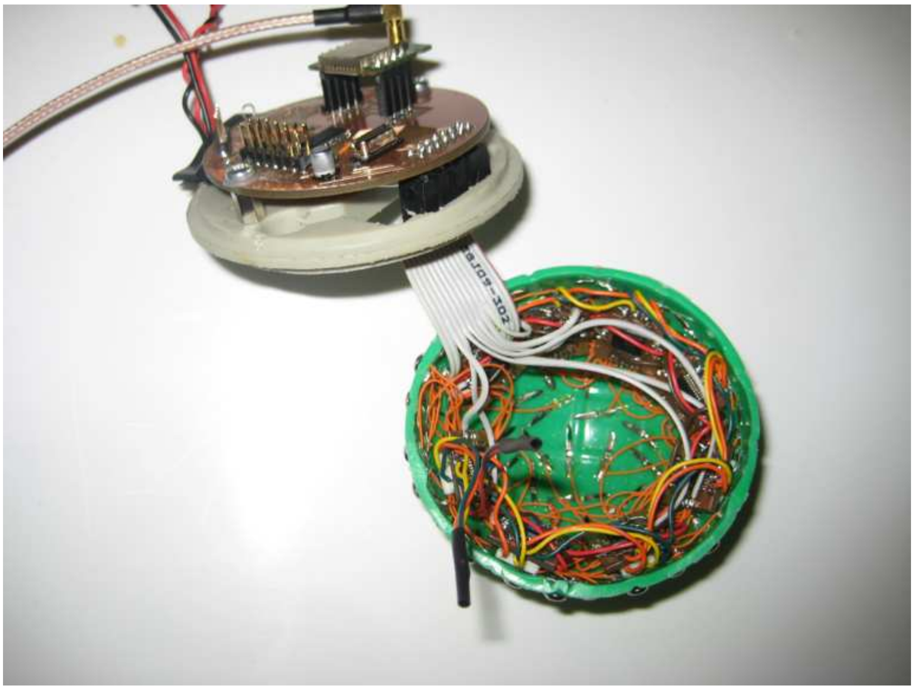
(a)



(b)

Figure 4.21: Spherical Digital Foam prototype version two electronics wiring: (a) Internal view of half plastic sphere exposing wiring of eight ADC integrated circuits. (b) Microcontroller, battery and orientation sensor installed (Inertia Cube 2 later upgraded to Inertia Cube 3).

(a)



(b)

Figure 4.22: Spherical Digital Foam prototype version two with wireless communications: (a) Top view of electronics with antenna attached to bluetooth module. (b) Close up view showing coupling between ADC chips attached to the green plastic half sphere and the microcontroller board connected via communication wires.

density used. A low density conductive foam material was selected that is not so significantly affected by this property.

The manufacturer technical information (provided in Appendix D) describes this property as ”Residual compression set” and with the low density conductive foam selected at a temperature of 70 degrees Celsius and 50% humidity it will return to 90% of its original size immediately, while the remaining 10% will take a maximum of 24 hours to return. Although this might sound like a very slow return rate, in practice it was found that it has not caused significant problems. Firstly, only after extreme compression will the conductive foam take this long to return, in practice this can be avoided and perhaps a mechanical stop can be added to prevent this in future. Secondly, the conductive foam used in Digital Foam is encased by a non-conductive layer that does not suffer from the slow residual compression effect. The non-conductive foam acts as a spring to pull the conductive foam back to the original shape. This effect was observed in the initial prototypes and might be exploited if commercially produced. It is envisages that a bonding between the two foam types might further support this functionality.

Unlike the Phantom [MASS94] and other active haptic devices, the response of Digital Foam is not controlled by the computer and does not support dynamic material emulation. This limitation may be overcome by incorporating actuation into the foam design. Being able to computer control the foam's shape dynamically would allow interesting functionality and might be a direction of future research. Another consideration is that the foam material springs back, unlike clay, so the shape is not retained. Using actuation would overcome this as well.

Using an insulated foam sensor design has been a successful approach for this research. Using a design that employs a single sheet of conductive foam was not as successful because surrounding sensors measurements are affected and therefore inaccurate, as previously described. It may be possible to overcome these inaccurate measurements by employing an algorithm that predicts the physical response of the foam to compensate for this. At this time, insulating using conductive foam provides the best performance and is the current preferred solution.

This chapter has described the process used to find a sensor that can be used to create a new input device capable of capturing sculpting-like operations. A number of alternative sensors were considered, leading towards the development of a conductive foam based input device named Digital Foam. A summary of the properties that describe the four prototypes developed is provided in Table 4.4. Following this, the design and implementation details of four prototypes were presented, each following either the Flat Digital Foam or Spherical Digital Foam physical design.

Prototype	Sensor Count	Communication	Frequency	Classification
Flat Digital Foam V1	100	Bluetooth	30Hz	Elastic
Flat Digital Foam V2	121	RS232	30Hz	Elastic
Spherical Digital Foam V1	21	Bluetooth	30Hz	Elastic
Spherical Digital Foam V2	162	Bluetooth	30Hz	Elastic

Table 4.2: Summary of prototype specifications

5

Digital Foam Interaction Techniques, Algorithms and Applications

This chapter begins with the presentation of new interaction techniques developed using the Spherical Digital Foam input device [SMIT08d]. The goal is to develop a modelling system that captures aspects of the sculpting metaphor and bring them into the digital modelling process. Following the interaction techniques section, a 3D cursor tracking algorithm developed to work within the fixed volume of Flat Digital Foam's interactive surface is presented. The algorithm exploits the physical response of the foam medium, combined with the raw data access to the row column sensor layout. This provides improved resolution compared to the number of physical sensors available, thus improving user control. This algorithm is further extended to support simultaneous multiple cursor tracking, exploiting Digital Foam's multi-touch capable surface. A supporting application written to demonstrate tracked cursors using a projected Flat Digital Foam surface is also presented. Finally, a colour picking application to demonstrate a practical application of the Flat Digital Foam input device is also described.

5.1 Interaction techniques

The purpose of the interaction techniques presented in this section is to develop a library of functions that can be used to allow the creation of 3D models using the sculpting-like operations discussed in Chapter 3. Figure 5.1 shows a user manipulating the Spherical Digital Foam input device and viewing the resultant 3D model on a LCD monitor. Although the investigations have been performed in a VR environment using a traditional LCD monitor,

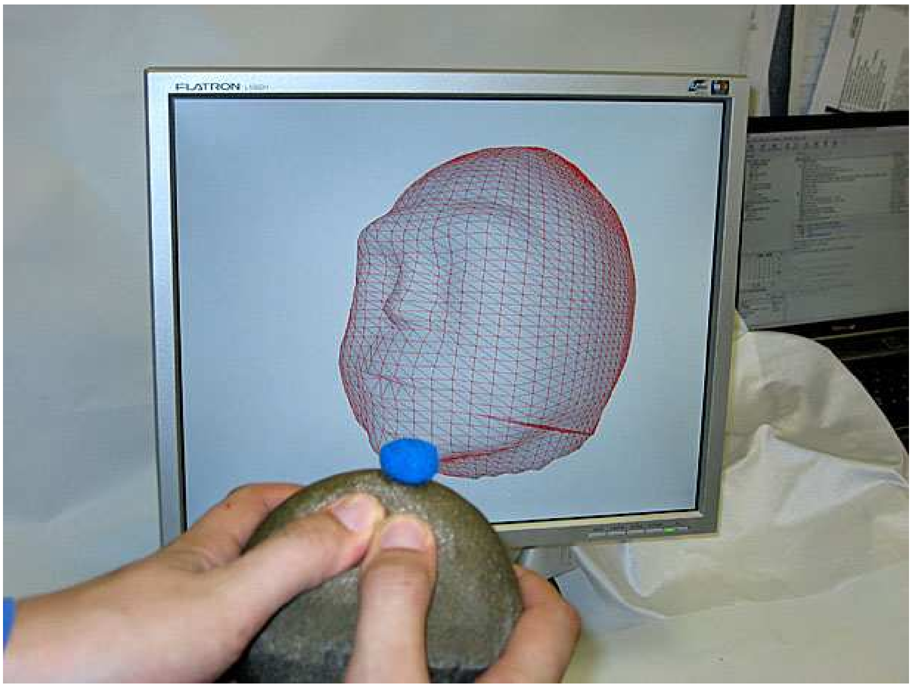


Figure 5.1: User sculpting a 3D model using the Spherical Digital Foam input device.

Spherical Digital Foam can also be used in an immersive VR mode for example using a head-mounted display. This section describes the techniques used to perform sculpting manipulation, navigation and command control without the need to put the device down or use any other input device.

5.1.1 Motivation

Creating and capturing 3D models is performed by graphic artists, industrial designers, researchers and those of many other disciplines. Current 3D modelling applications, such as Autodesk's 3ds Max or Maya, perform surface modelling using a range of input devices including keyboards, mice and tablets. Manipulation techniques are based around mathematical operations to alter surface shape and require extensive training to master. The goal is to develop a range of techniques that support intuitive 3D modelling interactions based on free-form sculpting operations, like those used when working with modelling clay. By using the clay sculpting metaphor for the interaction technique design, this endeavours to leverage people's pre-existing understanding of physical clay modelling. Digital Foam offers a new dimension to touch based surfaces that can be applied to 3D modelling. To reveal Digital Foam's potential, this dissertation has focused on developing, implementing and testing a number of interaction techniques to support 3D modelling. For the purposes of this investigation, the assumption that Digital Foam will be used as a sole input device has been made.

This was chosen so that the 3D modelling and interactions can be performed without the need for a keyboard or mouse, a similar requirement like when using virtual and augmented environments. This also removes the need for the user to put the input device down, freeing their hands to use a keyboard or mouse. Although speech input is another a possible command entry technology, the focus has been placed on a single device for command entry and direct manipulation of the object's surface.

5.1.2 Free-form sculpting

To leverage Spherical Digital Foam's ability to support 3D sculpting operations that are not possible using two dimensional devices, such as a mouse, a number of techniques that support free-form sculpting are presented. This is made possible by allowing each of the five digits (four fingers and thumb) on the human hand to uniquely contribute to the sculpting process. A mouse might be used to control pre-defined gestures but the same degree of freedom can not achieved. This sub-section discusses free-form sculpting in three parts: firstly, the process used to perform sculpting is presented, followed by a technique to expand the operating area of manipulation and finally an algorithm developed that allows free-form sculpting to be performed using existing 3D models.

5.1.2.1 Operation

Since the Spherical Digital Foam input device is not identical to a piece of modelling clay, a user can not use it in exactly the same way. The main difference between the two is modelling clay holds its shape after squeezing operations are performed and supports both additive and subtractive operations. The initial user interface was configured to capture the raw sensor data and update the geometry vertex locations to match. In this configuration, no permanent model modifications can be performed, i.e. when a user grasps the input device the model's shape is updated accordingly, and when they release it the original state is restored. However, a set of more permanent sculpting operations can be achieved through the use of clutching [HINC94] and software switches.

The modelling process starts using a fixed-base shape in which sculpting operations can be performed, currently the shape provided by the Spherical Digital Foam hardware is used (described in Chapter 4). A tilt-based clutching mechanism allows accumulative modelling operations. A user performs a sculpting operation by pressing the foam to the desired location, tilts the prop to a pre-defined angle (currently set to 20 degrees) and releases their finger. Each of the vertex positions are stored and the process can be repeated indefinitely. An example result of the clutching operation is shown in Figure 5.3.

The process described so far allows accumulative sculpting to be performed in one direction. In order to support both additive and subtractive processes, the manipulation direction (push in or pull out of the 3D virtual model) can be set, allowing the inverse operation to be performed. This technique is based on the observation that artists commonly attach and detach clay to a physical model during its creation. The user can change the direction by toggling a menu option (described in detail in Section 5.1.5). Figure 5.2(a) and Figure 5.2(b) shows a resulting sculpting operation depressing the left cheek.

5.1.2.2 Modifying existing models

To extend the functionality of the free-form technique, an algorithm that allows sculpting to be performed on existing 3D models was also developed. Firstly, a 3D model is loaded into the software, then a mapping between the Digital Foam sensors is performed, allowing semi-direct manipulations to be performed. This mapping is referred to as being semi-direct because the input device shape is not the same as the 3D model, yet a spatial mapping is maintained between the two.

To achieve the mapping between the 3D model and Digital Foam, a set of rays aligned with each of the conductive foam sensors are cast from the centre of the 3D model to find the intersection points on the outer surface of the 3D model (Figure 5.2(c)). Once each intersection point is found, an index to each vertex is stored for later use. The length of each Digital Foam sensor is mapped directly to these intersection points (as described in Equation 5.1) allowing the user to modify the 3D model by pressing the Digital Foam surface. The new vertex location (P') is found by translating the original position P in the direction of the ray using the foam length as the scalar value.

One limitation of the automated technique described above is the assumption that the model is a volume that has a centre of mass in a fixed volume. For example, if the model is a flat plane surface the algorithm would fail to find any intersection points. Manually specifying the centre point location is one method that can be used to over come this problem and allows non volumetric surface to be modified.

$$P' = P * (su * fl) \tag{5.1}$$

P' = New vertex location after manipulation operation.
P = Intersection point on model's outer surface.
fl = Current length of the foam sensor.
su = Normalized Digital Foam vertex location.

5.1.2.3 Operating surface area

The resolution provided by the Spherical Digital Foam's hardware is still relatively low in comparison to the polygon counts used when creating modern 3D models. To increase the working area between the physical spacing of the hardware sensor and the area manipulated on the model, an algorithm has been applied that allows a large area of the virtual model to be modified. One solution to this is to modify a group of polygons using a function to create a curved indentation that allows the new deformation to blend in smoothly (shown in Figure 5.2(b)). Firstly, the closest surrounding vertices are found within a user defined radius. To achieve this function a search to find the surrounding vertices for each intersection point is performed and stored in ascending order, based on length from the intersection point (P) to each vertex (V) on the model. For each vertex (V) within the user defined radius V' is found (the set of new vertex locations) by scaling the foam length (fl) by length between the intersection point (P) and the vertex V, see Equation 5.3. Using this function the furthest vertex within the predefined radius has no modification, other shape algorithms could easily be applied to achieve different effects as desired.

$$V' = V * ((su * (fl * |fd - vd|^2 * c) \tag{5.2}$$

V' = New vertex set after manipulation.
V = Current vertex set.
su = Direction pointing out from the centre of the model.
fd = Length from the furthest vertex to P.
vd = Length from the current vertex to P.
c = Scale factor.

5.1.3 Half hemisphere operation

When a user performs sculpting operations, a commonly observed problem is that a user's fingers and thumb may cause depressions in more than one location on the foam surface. This is problematic since these could be interpreted as unwanted modelling gestures. For example, when a user performs sculpting operations at the front of the sphere using their thumbs, the fingers are located at the back of the sphere causing depressions at both the front and the back, as shown in Figure 5.3(a).

To overcome this problem a technique was developed that divides the sphere's operating surface into two hemispheres, front and back. All vertices located on the front hemisphere relative to the user's view point remain active, while those behind are made inactive (Fig-

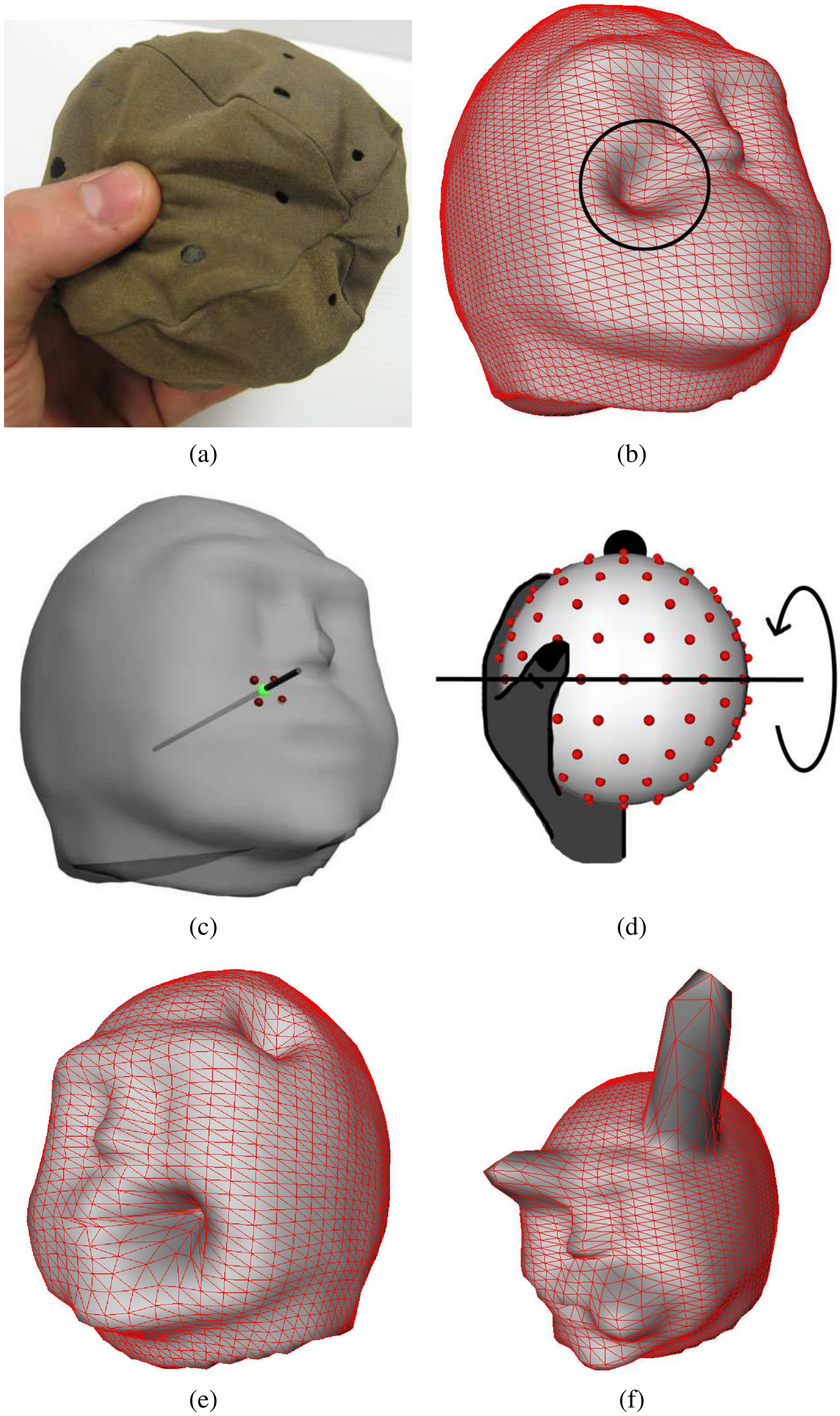
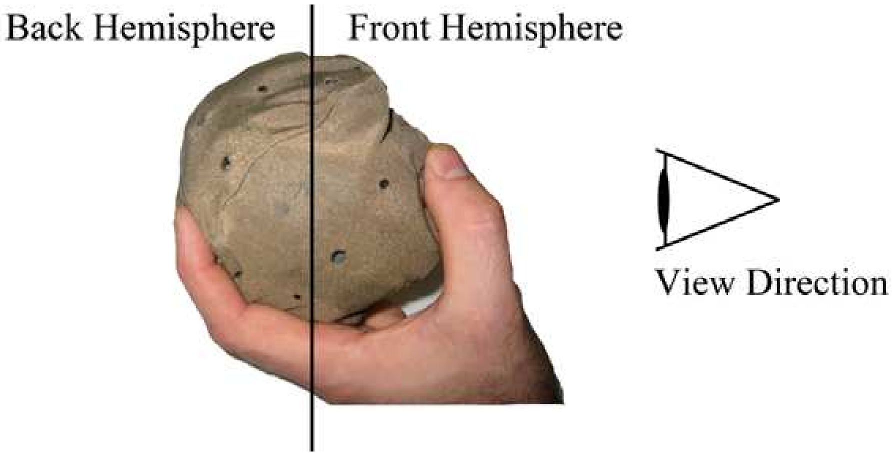
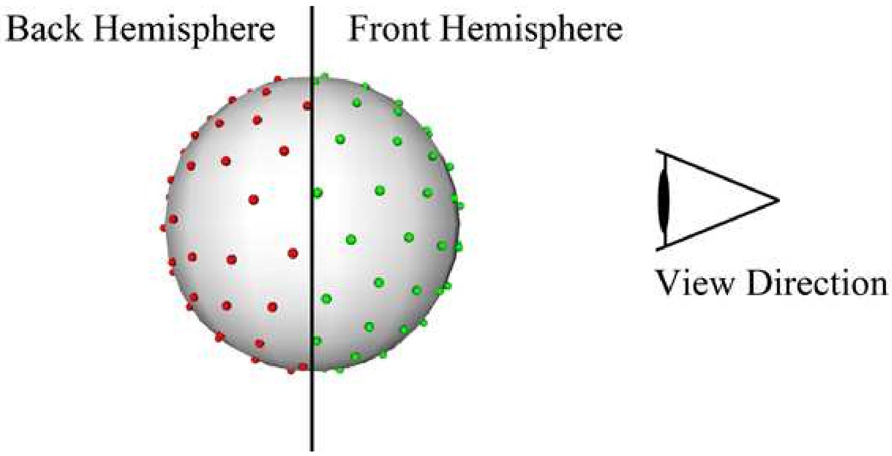


Figure 5.2: Free-form sculpting operations: (a) User sculpting with Spherical Digital Foam. (b) Working area increased with curved indentation. (c) Ray intersection finding aligning surface on model. (d) Clutching performed by using a tilt operation to store vertex locations. (e) Clutched free-form sculpting to push area inward. (f) Clutched free-form sculpting to pull area outward.



(a)



(b)

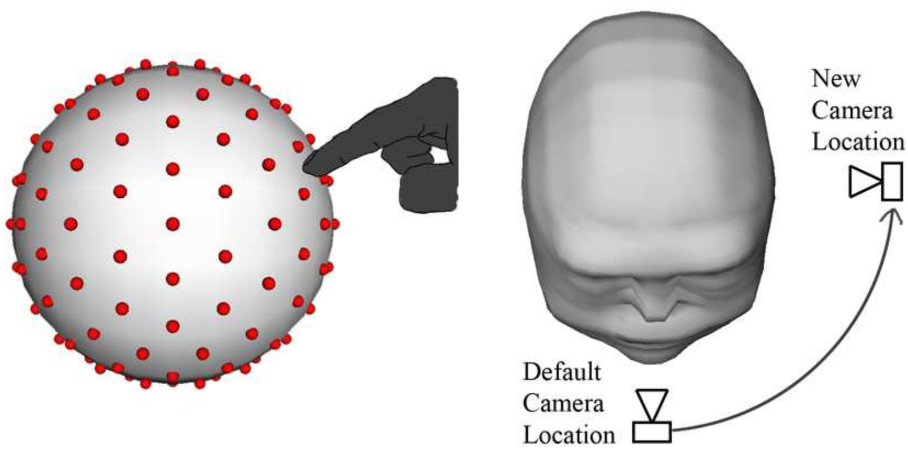
Figure 5.3: Half hemisphere operating technique: (a) User performing sculpting with their thumb, unwanted finger presses at back of sphere. (b) Half hemisphere correction being performed, inactive vertices shown on left side in red, active vertices shown on right side in green.

ure 5.3(b)). On initialization, the user specifies the front orientation and can not move their head position or orientation during operation (additional trackers are required on the user's head to achieve this). As the user rotates the Spherical Digital Foam input device, the virtual model's orientation is updated in real-time using the internal orientation sensor. To maintain the half hemisphere operation, all vertices that are in front of the centre point are flagged as active while those behind are inactive. This operation overcomes a significant user interface problem when operating Digital Foam allowing easier operation and increased control during modelling. The half hemisphere operation can be applied to work in conjunction with other techniques allowing stacked operations to be performed. For example, half hemisphere operation can be used in conjunction with sculpting or menu click operations.

5.1.4 Camera view control

Supporting control of the camera location is an important function when sculpting a 3D model. To support this function using Spherical Digital Foam, a new camera view control technique has been developed allowing a user to quickly and intuitively move the virtual camera's position. Figure 5.4 depicts the operation of the Spherical Digital Foam in the camera view control mode. While in the camera view control mode, a user touches any part of the surface of the sphere and the camera viewpoint will be shifted to the matching location. When multiple sensor readings (depressions) are detected, the foam sensor with the shortest value is used to determine the camera position. The direction of the camera is determined in a similar fashion to the orbital view algorithm [KOLL96]. A bounding sphere is created around the virtual model and the direction of the camera is set to look at the centre of the object. The user can also control the zoom of the camera based on the pressure of the touch. As the user increases pressure on the Digital Foam, the camera zooms in closer, and as the user releases, the zoom location returns. After the user stops touching the Digital Foam surface altogether, the camera's default location is left at the last intersection location.

This camera view control leverages a spatial reference between the input device and the model in the virtual world. For example, when touching the back of the device the corresponding location in the virtual world is used. This technique might be extended further to employ the clutching mechanism previously described, one reason this was avoided is that when performing the tilt operation the spatial reference becomes misaligned, and although it is returned once the clutching operation is finished confusion is easily introduced.



(a) (b)

Figure 5.4: Orbital camera view control: (a) User controlling the camera location with the touch point, zoom is performed using touch pressure. (b) Top view demonstrating the camera transition used for the touch point.

5.1.5 Menu control

When a number of techniques are combined together, the ability to change between the different operating modes became necessary. There have been a number of techniques developed that explore the use of two-dimensional devices for interactions in three-dimensional environments, and make appropriate mappings by performing translations and orientations between the two [SHOE92]. Specifically, there are a number of menus that have been developed for three-dimensional environments. Bowman et al. used pinch gloves to control their TULIP menu system [BOWM01]. Menu items are mapped to each finger in the virtual environment. Circular menus have been employed in virtual environments. HoloSketch [DEER95] uses a 3D pie menu with concentric menu items that can be activated with a wand. Liang et al. presented the JDCAD 3D modelling system [LIAN93] that uses a spherical and ring menu for object selection. The idea is further evaluated and developed by Gerber and Bechmann [GERB04, GERB05] into a hierarchical spin menu as a context menu in a VR environment. Reitmayr et al. presented the iOrb [REIT05], a hand-held input device that tracks orientation. Menu operations are controlled by first mapping three orientation values to a 2D coordinate system with orthogonal axes based on the user's current arm pose. These values are then mapped to different menu widget styles. Two selection methods were used: one uses a time-out value and the second uses a predefined threshold angle allowing menu selection operations.

Given the functional uniqueness of the deformable surface that Spherical Digital Foam provides, a custom menu system was developed allowing spherical Digital Foam to operate as a sole input device for command entry. The navigation of the menu is designed to be intuitive, quick and easy to use so that minimal user training is required. There are a number of challenges that need to be addressed to use Digital Foam as a sole input device for both command entry and direct manipulation. From here onwards, all direct forms of model interactions such as free-form sculpting and camera view control are described as *interaction modes*. A technique is described here that allows the user to transition from any interaction mode into a *menu mode* without using additional input devices.

To transition from interaction mode to menu mode the user rotates the input device upside-down so the roll or pitch is beyond a predefined threshold value (currently set to 90 degrees and shown in Figure 5.5(a)). Once in the menu mode, the user can navigate through menus by rotating the input device around the heading (vertical) axis. The current menu is configured to have 10 menu items allowing the user to select different interaction modes. As more items are required, a hierarchical menu can be employed to expand the functionality. To scroll through menu options the transition interval is set at 20 degrees. When the user rotates around the heading axis the selected menu option changes from one menu option to the next, every twenty degrees (Figure 5.5(e)). Currently ten menu items are displayed on two rows with five menu items on each row. A transition from row one to row two occurs when the last item in row one is reached. By rotating the input device beyond the last item in row two, a transition to the first row occurs.

Once the correct option is selected, a menu selection operation is required. To achieve this the Digital Foam sensor is used. By squeezing the input device with one or two hands, a menu selection operation is performed. In software this is determined when the average value over all sensors drops below a predefined threshold and a "click" event is generated. Finally, once the option has been selected and clicked, the menu is hidden and the selected interaction mode becomes immediately active.

To re-enter the menu mode, the input device orientation must first return to a near upright position so that the rotation values are above the predefined threshold. Once this has occurred the device can be turned up-side-down again to enter menu mode. Figure 5.5 shows the different states of the menu selection operation.

One limitation of this technique is that when operating in modes that map the orientation sensor directly to the model, the menu mode may be accidentally entered. Although this is a limitation, during my use rotating around the heading is commonly used for model navigation and both pitch and roll are unaffected until they pass the threshold value (currently set at 90 degrees).

5.1.6 Rotation

Controlling the rotation of the model is a another very important function. To manipulate the rotation using Spherical Digital Foam, two separate modes of operation are employed. The first uses a direct mapping between the values of internal orientation sensor and the 3D model allowing heading, pitch and roll to be easily controlled. The continuously updating model rotation can also be used in conjunction with other techniques such as free-form sculpting to adjust the current view angle. A menu option can be toggled to turn rotation on and off, however this mode is stateless and the model can not be set to a user defined position once this interaction mode is left.

To overcome this problem, a second rotation control mode that allows a default rotation angle to be set using clutching [HINC94]. The activation of the clutching is achieved by detecting a squashing gesture on the Digital Foam surface. When using "set rotation", no rotation transformations are performed until the user begins squeezing the Digital Foam input device. When the desired operating angle is selected the user stops squeezing the input device and this angle is recorded and used as the default model orientation for all other interaction modes.

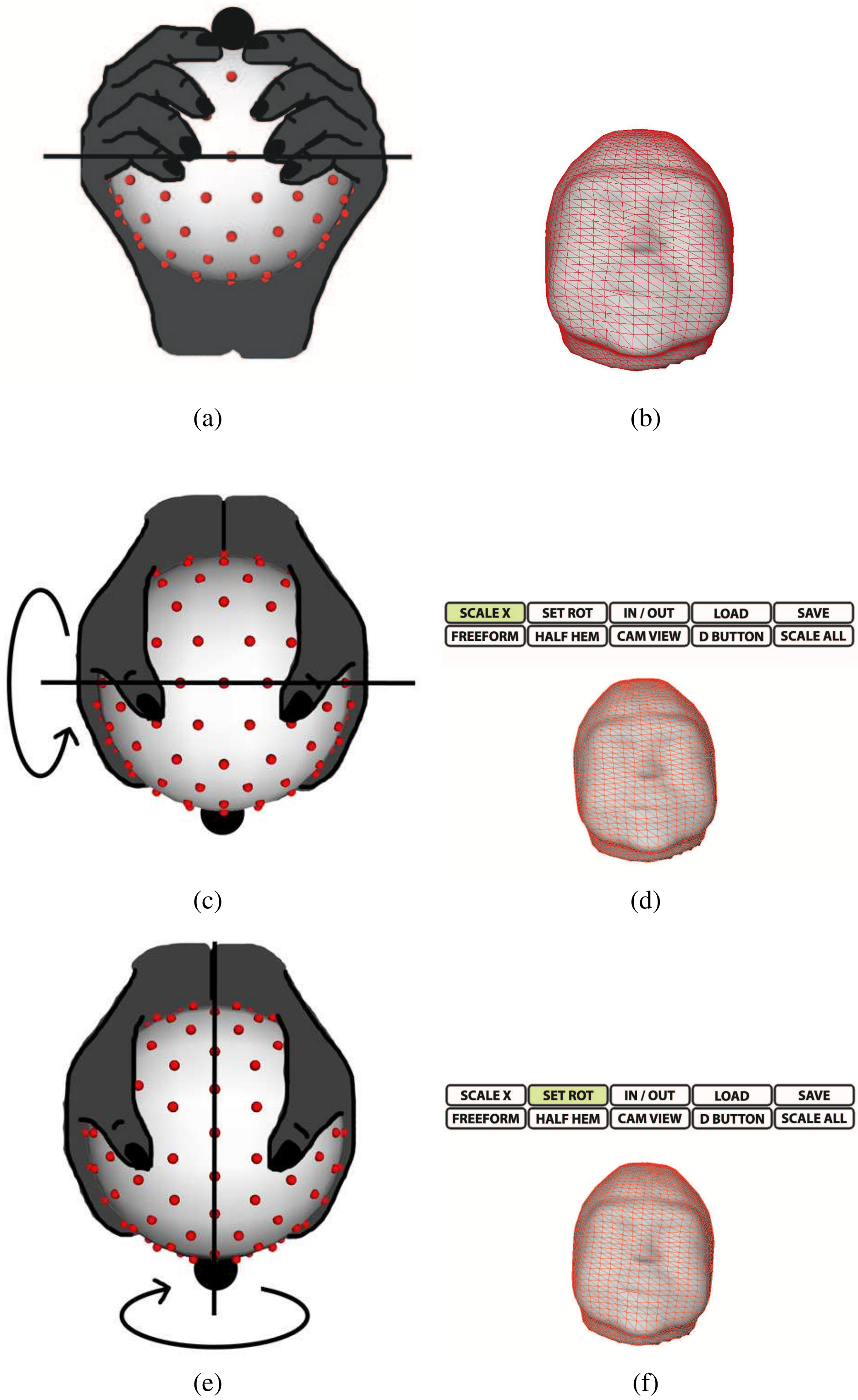


Figure 5.5: Menu command entry: (a) Interaction pose prior to menu operation. (b) Operating in interaction mode. (c) User rotates prop up-side-down to display the menu. (d) Menu is displayed. (e) User rotates around the vertical axis to select menu items. (f) Scrolling menu item is highlighted.

5.1.7 Scale

A number of scaling functions were implemented to allow manipulation of the virtual model. Eight separate scale operation have been employed using Spherical Digital Foam. Each is activated by squeezing the Digital Foam's surface to directly alter the scale value. The scale can be altered on the X, Y or Z axis separately or a combined operation where the overall model's size is altered. The direction of scale can also be toggled via the menu. Figure 5.6 demonstrates a range of different scale operations performed on a model.

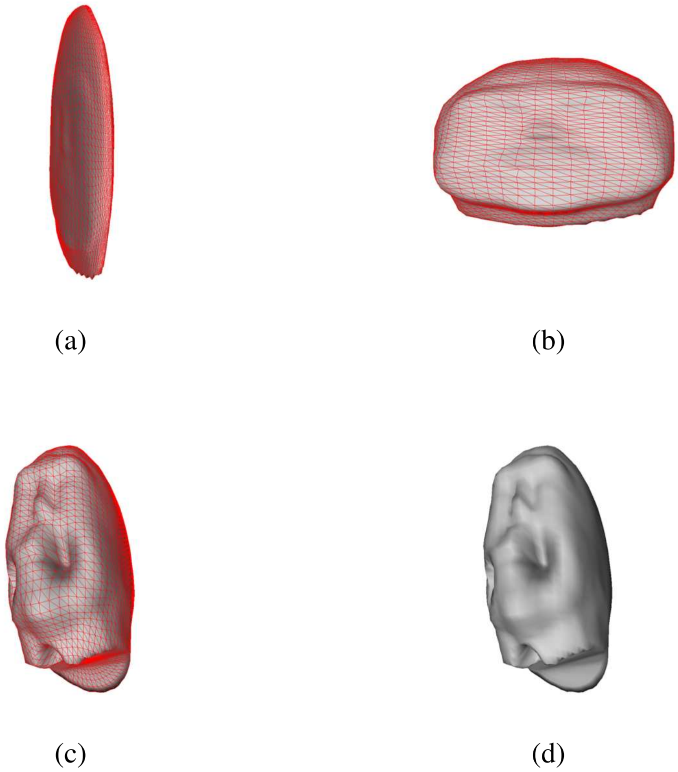


Figure 5.6: Scale operations performed on different operating axis: (a) Scale X axis. (b) Scale Y axis. (c) Scale Z axis. (d) Scale with surface material.

5.1.8 Orientation marker identification

When using the menu system, free-form sculpting or the camera view technique, it is useful to have a marker on the physical device to identify the top of the sphere. To facilitate this identification, a physical marker is attached to the input device. The physical marker can be seen in Figure 5.1 immediately above the user's thumbs on the Spherical Digital Foam input device. A matching software marker can also be toggled on and off via the menu, although features on the model are often sufficient for identification. This simple technique further assists the spatial reference between the physical prop and the 3D model, an ongoing goal of all the techniques presented in this section.

5.1.9 Load and save function

Existing models can be loaded into the scene as previously discussed. The entire scene graph can also easily be saved by selecting the appropriate menu option. Currently files are saved in SGIs Inventor format[1] which is easily convertable to other model formats as required. Many of the figures in this Chapter were generated using the numerous 3D model files created during the experimentation with each of the techniques.

5.1.10 Proposed dynamic button allocation technique

In conjunction with the above implemented techniques, a final technique is proposed for use with Digital Foam. The functionality of the techniques is described with a number of possible implementation suggestions. A number of questions are also raised as to how the algorithms might be developed and if they are practical.

The creation of the new higher resolution Spherical Digital Foam has inspired a new technique concept not possible using the original Spherical Digital Foam. I propose that unique areas of the foam's surface can be configured in real-time to set up active regions for different operations. For example, the system prompts the user to configure a "left click", and the user would depress the desirable area of the spherical prop for their personalized "left click" operation. The application would then record the surface selected and the pressure used so that intelligent decisions could be made to interpret a "left click" operation. Some kind of intelligent reasoning techniques such as Hidden Markov Models or a Neural Network might be adopted to implement this functionality.

5.1.11 Summary of interactions

Techniques presented in this section have been developed to support 3D modelling tasks using Spherical Digital Foam as a sole input device. The free-form sculpting and clutching technique allows surface manipulations of existing 3D models to be performed while leveraging a spatial mapping between the hardware device and virtual model. Additionally, a tilt-operated clutching mechanism is implemented, allowing the operations to be accumulative. The half-hemisphere technique, designed to assist a user while performing sculpting

[1] ftp://ftp.sgi.com/graphics/SGIIMAGESPEC

operations, has been presented and implemented. This allows more intuitive operations to be performed by filtering unwanted press locations on the Digital Foam's surface. Also presented is the implementation of a camera view control mechanism that allows a user to simultaneously move the camera around in an orbital motion whilst controlling the zoom parameter with a single touch point. A menu control system is presented that allows Spherical Digital Foam to perform command and control operations as a sole input device.

A unique aspect of the interaction discussed in this section is that Digital Foam can be used as either an absolute or relative device. An example of each mode can be seen when considering the "Camera View Control" and the "Free-form sculpting" techniques. When using the camera view control technique the device is operating as an absolute device. This is evident as there is no form of clutching being used with this technique, the entire operating range of the device is mapped to the maximum distance being viewed in the 3D scene. When considering the free-form sculpting technique the Digital Foam device is operating as a relative device with clutching. This is done because the physical shape of the Digital Foam device, a sphere, is not the same as the 3D model that a user is creating.

5.2 Digital Foam algorithms

This section describes an algorithm developed to track a 3D cursor using an array of ordered pressure sensors, such as the Flat Digital Foam surface. However, this algorithm could also be applied with other pressure sensitive devices that provide the same, or similar data.

5.2.1 3D cursor tracking

The position of a single finger press can be tracked by searching over each foam sensor reading to find the one with the deepest depression recorded. Once found, the X and Y location is known based on the physical location of the sensor. For the depth (Z axis), the raw sensor reading from the foam sensor is used. This is a quick method that can be used to achieve single cursor tracking. The current Flat Digital Foam prototype made up of 121 foam sensors does not provide fine-grained control of the cursor's position due to the relatively low sensor density. The resolution is described as being low if the user's finger size is compared to the 18mm spacing between each pressure sensor. For example, if the user slides their finger across the touch surface and a transition between two sensors occurs, the minimum distance the cursor moves is 18mm. Although this technique is functional, it does not provide smooth output or fine-grained control of the cursor position. One solution to this problem is to increase the sensor density, thus reducing the minimum distance a cursor will move at any point. However, there are limits to how dense the sensors can be placed, and so other improvements are still required.

To further improve the smoothness of operation, an algorithm that utilizes the surrounding pressure values to increase the tracked resolution has been implemented. This algorithm is functionally similar to those used when performing "blob detection" in vision systems [RASM96, DORF01]. Figure 5.8(b) depicts a cross section of the Digital Foam surface with a single finger depression. This highlights that the foam depression does not wrap tightly around the user's finger (or other object), and causes a group of pressure sensors to be partially depressed. Figure 5.7(b) shows a finger press location that is not directly above a terminal and emphasizes the sensors to the left and right side of the deepest depression point are not equal. This physical property of the foam pressure sensors is leveraged to provide more accurate cursor tracking.

Both Flat Digital Foam prototypes use evenly spaced terminals in a row-column layout, Figure 5.7(c) depicts a group of nine sensors. Here it is assumed the middle sensor, s_5, has the deepest depression point, and then apply Equation 5.3. Equation 5.3 describes the calculation used to find the new cursor location using vector mathematics.

$$CP = s_5 + \sum_{i=1}^{9} (d_i * |sp_i|) \tag{5.3}$$

CP = cursor location.
d_i = Direction vector pointing towards s_i from s_5.
sp_i = Normalized pressure sensor reading.

The accumulation of each surrounding pressure sensor provides a weight in the sensor's respective direction based on the current pressure value. This is used to alter the location of the cursor until the final position is found, providing a position in three dimensions (X,Y,Z) within the fixed volume of the Digital Foam's working area. This operation is comparable to techniques used in vision tracking to find the center of mass during blob detection as described by Blum et al. [BLUM02].

5.2.2 Multi-cursor tracking

The 3D cursor tracking algorithm was also extended to support multiple cursor tracking. The Digital Foam architecture provides access to each sensor reading uniquely, allowing the surface to be divided into sub-sections for each cursor tracked. Figure 5.8 displays four cursors with the divided tracking areas displayed. Using the single cursor algorithm, the deepest depression on the Digital Foam surface is found. Unlike a traditional touch screen,

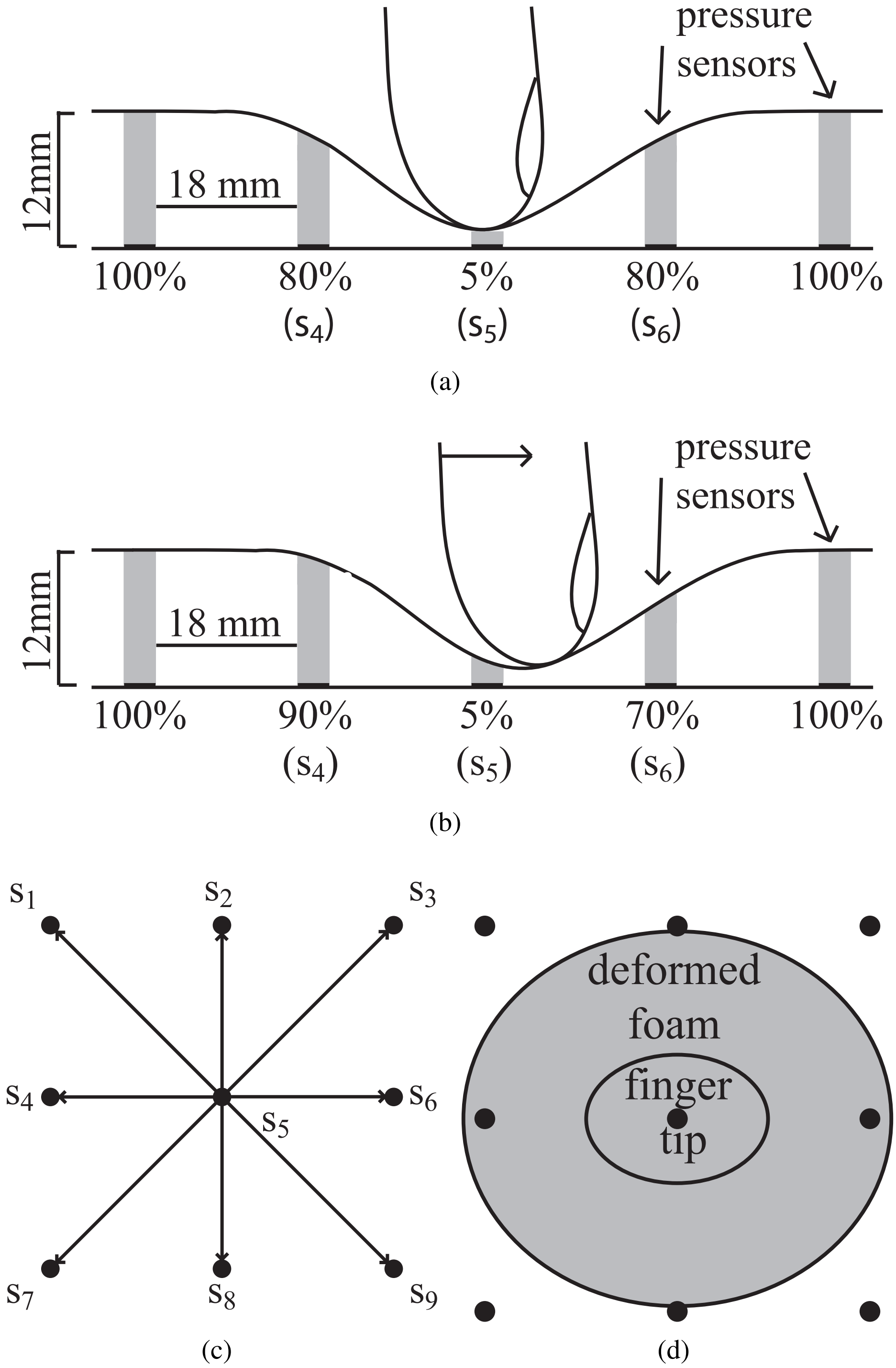


Figure 5.7: Physical foam properties: (a) Finger pressing on foam surface above terminal. (b) Finger pressing on foam surface offset from terminal. (c) Top view of depression area on foam surface. (d) Sensor Layout with direction vectors form centre terminal to outer terminals indicated.

Digital Foam does not return a combined center of mass based on all the depression points, rather it provides each sensors value allowing more complex multi-touch point captures to be calculated. The multi-cursor algorithm allocates a sub-section (made up of the immediately surrounding sensors) for each depression point. Using this algorithm the location of the cursors can only be altered by performing dragging operations.

To demonstrate the operation of multiple cursor tracking, a demonstration application was developed allowing new cursors (displayed as coloured spheres) to be created in real-time. The bottom right corner of the Digital Foam tabletop surface is dedicated to creating new cursors (large idle cursor in the right bottom corner of Figure 5.8). Users create new cursors by dragging the idle cursor into the active area (shown in Figure 5.8). Each new cursor created has a unique identifier, and a unique colour is assigned to each cursor for quick identification. This algorithm, like the single cursor algorithm, calculates a 3D position using the surrounding sensors to find an interpolated position with greater resolution compared to the physical sensor spacing of the hardware.

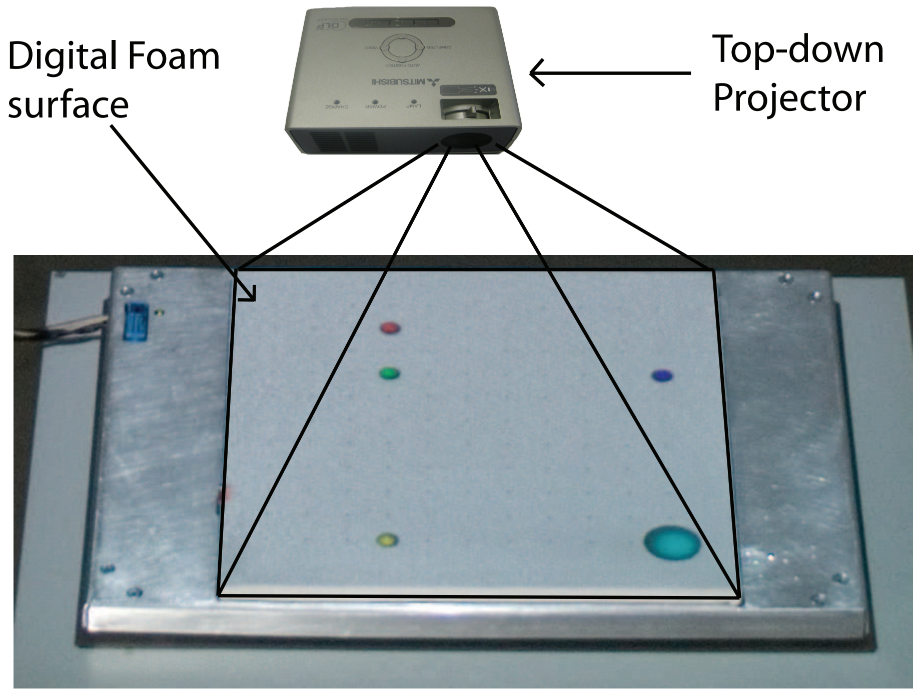
5.2.3 Cursor tracking discussion

The single cursor algorithm allows a user to touch the Digital Foam surface and the location is easily determined. If two points of depression occur, the algorithm currently picks the more significant (deepest) press location. Alternatively, the average of the two points could be used as it is done with single-point touch screen hardware.

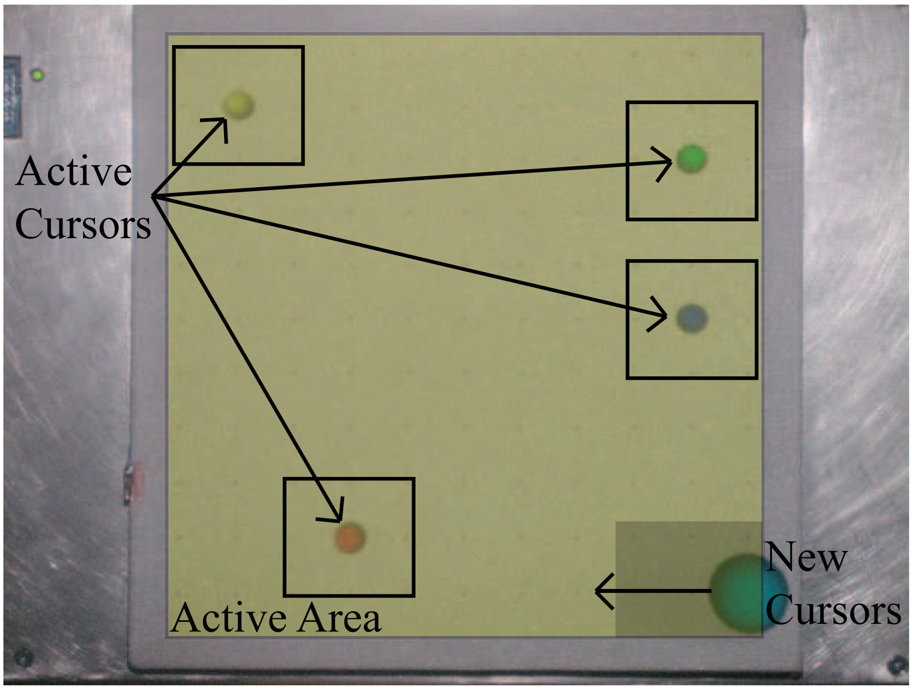
The multiple cursor tracking algorithm is scalable and the total number of cursors is only limited by the number of pressure sensors and the overall surface area. In comparison to the DiamondTouch [DIET01], which employs multiple user tracking, our implementation does not identify who is touching the table, but maintains a unique identification number for each cursor generated. In operation, any user can move any cursor to a new location, with the cursor's position only updatable using a dragging operation. This is unlike the DiamondTouch, which identifies a user's touch point, so dragging operations are optional but not mandatory.

An advantage to the Digital Foam setup is users are not tethered in any way to the electronics. When configured as a tabletop display, this allows unrestricted movement around the tabletop surface. Additionally, the number of unique cursors is only limited by the sensor density and physical size. Using the current prototype with a surface area of 44100mm^2 it is possible to manipulate ten cursors simultaneously without significant collision problems.

One notable limitation of the Digital Foam surface is that when two touch points (cursors) are closely located (within 54mm of each other on our current prototype) the surrounding sensor readings become shared, which reduces user control. Although this is inconvenient it



(a)



(b)

Figure 5.8: Multi-Cursor tracking application: (a) Projected environment setup. (b) Multi-cursor test application, new cursors are created in real-time by dragging the bottom right idle cursor into the active area.

can be avoided during operation and may also be reduced as the sensor resolution increases.

The concept of using Digital Foam as a pressure sensitive tabletop or tablet based interactive surface has been presented. Additionally, the design of two algorithms to track 3D cursor locations for a pressure sensitive surfaces are presented. The cursor tracking exploits the physical foam property causing a number of pressure readings around any one touch point providing increased cursor tracking accuracy. Both algorithms have been implemented and tested using the Flat Digital Foam with projected graphics on the surface supporting real-time interactions.

5.3 Colour picker application

To demonstrate a practical application of the Flat Digital Foam surface, a small colour picker application has been written that allows a user to a mix colours using their fingers. This application demonstrates the use of Digital Foam's multi-touch surface, using the pressure information to perform an interaction technique that is not possible using a traditional fixed-type touch surface.

The Flat Digital Foam was set up using the previously described projected environment (see Chapter 4 Section 4.3.2). A simple interface was configured to display a colour palette, two colour quantity displays, a mixed colour display and an accept button as shown in Figure 5.9. A user can mix two colours from the colour palette to create a new custom colour. The user selects two colours using their fingers and controls the quantity of each using the touch pressure. As the user presses harder the quantity increases, and decreases as the pressure is released. The current quantity of each colour is mixed and displayed. When the desired colour is achieved, the user can press the accept button and the custom colour is stored in a spare location on the colour palette. This operation can be repeated, allowing the custom colour to be used as one of the two base colours allowing subtle changes in colour to be made.

This widget was developed to give an example of how Flat Digital Foam can be used to implement an intuitive interaction technique. It is unique in the manner that a single touch point is used to firstly select a colour, while the quantity value is controlled without moving to the left of right but only by altering the pressure of the touch point. The same functionality might be achieved using a fixed pressure sensitive surface, however unique haptic feedback is provided by the feel of the foam surface.

The technique used to interact with the surface is functionally different from a graphics tablet, such as a Wacom ®[2], which uses a hand-held pen with a pressure sensitive tip.

[2] http://www.wacom.com/

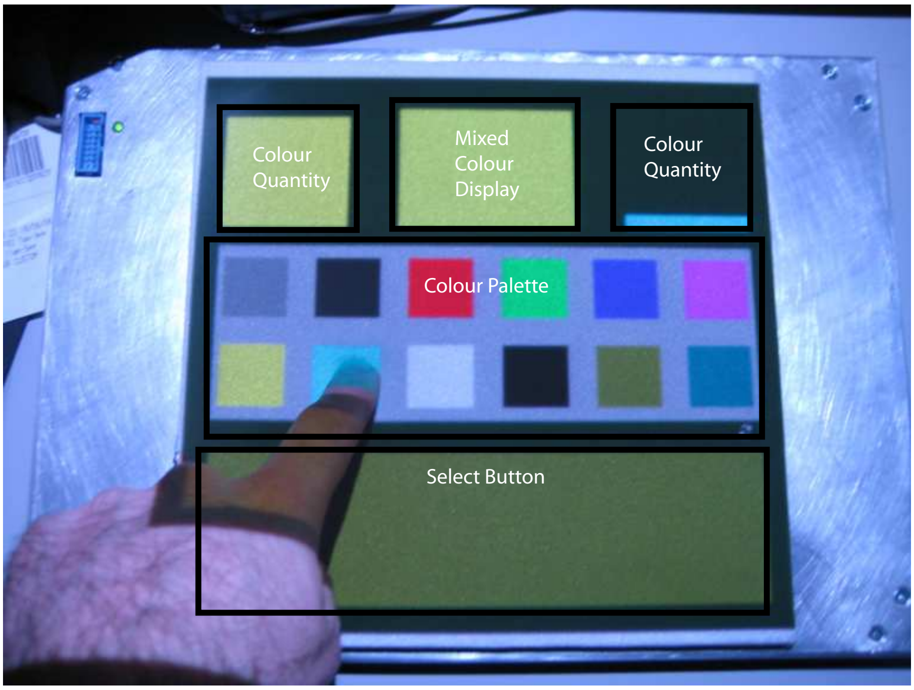


Figure 5.9: Colour picker widget allowing a user to mix custom colours with multiple touch locations and pressure sensitive surface.

With the Digital Foam surface a user interacts directly with the surface using their fingers rather than holding a pressure sensitive pen. Using this technique, it is possible for a user to mix multiple colours with separate fingers of one-hand controlling the mixed colour with the touch-point pressure of each finger simultaneously. To achieve the same function with a graphics tablet, a user would have to hold two pens or add the colour components sequentially.

5.4 Summary

To explore the uses of Spherical Digital Foam, the design of interaction techniques that can be used for sculpting, geometry capture and navigational operations have been presented in this chapter. One of the goals is to develop a modelling environment allowing natural artistic operations to be expressed. To support this, the free-form sculpting and clutching techniques allow a unique 3D modelling process to be performed. This technique is further supported using the half hemisphere operation, allowing unwanted depressions caused by holding the input device to be avoided. A range of commonly used functions such as scale and rotate are also possible using Spherical Digital Foam. An orbital navigation technique allows to a user to quickly navigate and easily observe the model they are sculpting. To provide a means of command entry without the assistance of other input devices, such as a mouse or keyboard, a menu system was developed. Controlling the menu is achieved by rotating the Spherical Digital Foam for selection operations and squashing the device for clicking. The functionality presented in this section has been developed as a key group of techniques that begin to exploit and leverage this unique input device.

The physical form of the Flat Digital Foam input device offers a plethora of new human computer interaction techniques. I have presented an algorithm that allows the tracking of a 3D cursor within the fixed volume of the Flat Digital Foam device. This algorithm additionally provides a tracking resolution greater than the physical sensor spacing by using surrounding pressure sensors. This algorithm is further extended to support multiple cursor tracking, leveraging the multi-touch capability of the Digital Foam surface.

Finally, a colour picking application to demonstrate a practical use of the Flat Digital Foam surface is described. The techniques presented here provide a basic interaction functionality and by no means have covered every technique made possible using Digital Foam. The techniques have however addressed two significant research questions raised in this dissertation: "What interaction techniques can be applied allowing a range of different sculpting operations to be performed?" and "How can the proposed input device be used as a sole input device (i.e. without assistance of a keyboard or mouse)?". The solutions presented have been made possible using the novel Digital Foam sensor in both the flat and spherical physical forms.

6

Digital Foam Performance Evaluation

The Digital Foam prototypes developed and presented in the previous chapters have provided a proof of concept to facilitate an interactive three-dimensional surface using an array of conductive foam sensors. To date, there are two design layouts, Flat Digital Foam and Spherical Digital Foam (four prototype devices in total). The use of the Flat Digital Foam for use as a table-top or tablet-like device has been discussed, and a cursor tracking algorithm presented to support 3D pointing operations using the deformable interactive surface. A variety of free-form sculpting techniques have also been discussed that can be performed using the Spherical Digital Foam input device. Given the current state-of-the-art of Digital Foam, this Chapter establishes an initial benchmark performance (Established in Experiment 2) which is used to analyse the performance of the algorithms presented in Chapter 5 (Compared in Experiment 3).

This chapter begins by presenting a computer controlled apparatus developed to perform accurate and repeatable stroke operations on Digital Foam surface using a mechanical finger. Following this, four experiments performed to evaluate aspects of the Digital Foam Sensor are presented. The first two experiments presented capture the benchmark performance of the Flat Digital Foam sensor using two stroke patterns. The third experiment applies the 3D cursor tracking algorithm so that a performance comparison of the algorithm can be made. Finally, user experience data is gathered through a trial user study using the Spherical Digital Foam input device. The goal of this trial user study is to record observations that will assist the future design directions of input devices employing conductive foam sensors.

The focus of this evaluation chapter is to gain qualitative measurements that identify operating parameters of the foam-based input device prototypes presented in Chapter 4. Existing research and product datasheets describe the physical properties of conductive foams (provided in Appendix D), but the aim is not to remeasure these properties. Instead, the focus is on observing the conductive foam performance when employed in the Digital Foam's physical configuration, with the goal of assessing the feasibility of conductive foam based input devices. To achieve this, firstly a benchmark performance of the device needs to be measured and can be used to test the performance of the 3D cursor tracking algorithm. The following list summarises each of the specific evaluation goals addressed in this chapter:

- Measuring the repeatable performance of a stroke operation performed on a Digital Foam surface.
- Measuring the error rate observed between the physical location of a touch-point compared to the sensed position reported on the Digital Foam sensor.
- Measuring the performance of the 3D cursor tracking algorithm employed on the Flat Digital Foam input device.
- Gathering user experience data using the Digital Foam device.
- Identify conductive foam sensor guidelines and operational issues.

Although each of the designs are uniquely constructed, the foam sensors and electrical schematics are all similar in design. Selecting the most appropriate Digital Foam prototype for the first evaluation experiments was carefully considered. The flat design was selected over the spherical version because it simplifies the technical setup required for the repeated stroke procedure. When holding the spherical version, multiple touch points in the foam surface occur, as described previously in Chapter 5 Section5.1.3. This is undesirable when capturing the benchmark performance and unsuitable for testing the 3D cursor tracking algorithm. The second version of the Flat Digital Foam input device, described in Chapter 4 Section 4.3.2, was chosen for the quantitative performance testing, which was selected due to the robust design and ability to withstand more rigorous testing. Spherical Digital Foam was selected for the trial user study, so that user experience and acceptance information could be gathered that will assist in future developments of the Digital Foam sculpting system.

Another consideration for the evaluation process presented in this Chapter is the current prototypes are the first generation and have room for technical improvements. Both the electronics and physical construction are not in their optimal form and will be developed over time. However, in their current state the benchmark performance of the raw data can be captured and then compared to the performance with the cursor tracking algorithm in place. As the device performance improves it is expected that the overall performance will also be beneficial to the tracking algorithm performance.

6.1 Approach

Digital Foam is the first device to use an array of conductive foam sensors for the construction of a 3D computer input device. The functionality of the pressure sensitive surface introduced a number of challenges that need to be overcome in finding a suitable technique to measure Digital Foam's performance. The goal is to compare the position of the touch-point in the physical world to the reported position on Digital Foam's deformable surface while performing a repeated stroke operation.

Two approaches were considered for the experimental setup. The first technique proposed involves attaching a 6 DOF tracker, such as a Polhemus[1] active magnetic tracker, to a user's finger allowing the physical world position of the user's finger to be recorded and compared with the registered touch-point on the Digital Foam surface. The user would then be instructed to repeatedly drag their finger along a line on the Digital Foam surface. A disadvantage of this approach is that user error means a slightly different path would be followed on each stroke making a true repeated stroke difficult to achieve.

An alternative approach envisaged to overcome this problem is to construct a custom apparatus using a computer controlled mechanical finger. This apparatus setup will allow a repeated stroke to be performed, maintaining a fine-grained control of the position and speed parameters. Using this approach, the errors introduced by the human are no longer a problem. With either setup described, the desired goal is a repeated stroke operation being performed on the Digital Foam surface with the maximum repeatability accuracy. To assist with the selection, operational features of each system were identified. Table 6.1 provides a comparison of the required operations using the two different approaches.

With the data captured from either of these setups, the goal is to perform a statistical analysis that describes the error between the physical location of the touch point and the location registered on the Digital Foam surface. Once the benchmark performance is recorded, the same procedure will be performed using the cursor tracking algorithm producing another dataset that describes the error ratios. The two data sets can then be compared allowing an analysis of the performance to be conducted.

6.2 Apparatus setup

A computer controlled mechanical finger was selected as the most optimal testing apparatus. It was chosen because of the benefits outlined in Table 6.1. The design and construction of the evaluation apparatus introduced a number of challenges. Finding a device to provide

[1] http://www.polhemus.com/

Attribute	Computer-Controlled Mechanical Finger	Tracked Human Finger
Repeatability Accuracy	Virtually identical movements achieved (+- mill specifications).	A human finger can not guarantee the same movement. Tracking introduces additional errors.
Data Gathering	Position can be measured at the accuracy of the computer-controlled platform.	Position can be measured based on the accuracy of the 6 DOF tracking system used.
Efficiency	Evaluation process can be automated.	Requires a human to repeat the same operation many times, increasing the error.
Stroke Operation	Auto detect start and finish of operation.	Manually need to specify the start and finish of a stroke operation.

Table 6.1: Comparison between evaluation apparatus, using a computer controlled mechanical finger or a tracked human finger for the performance evaluation.

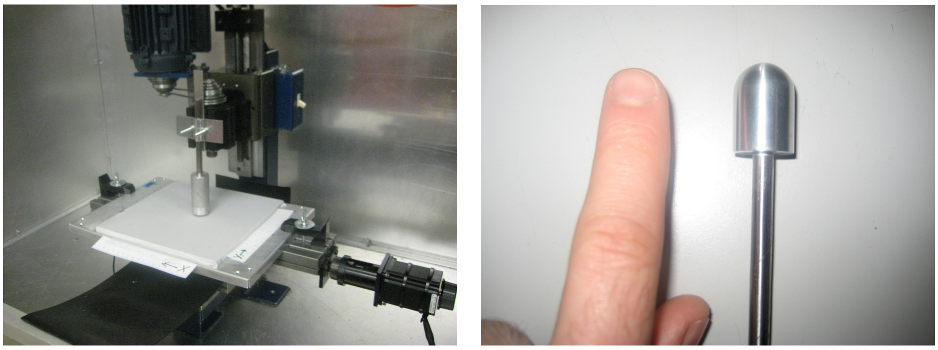
a mechanically controlled finger with a repeatable stroke requires a hardware platform that controls the location of the mechanical finger, and software that directs the stroke patterns and logs data. Both of these are described in the following subsections.

6.2.1 Computer controlled platform

Figure 6.1(a) shows the apparatus constructed to perform the evaluation procedures. The experimental setup consists of a sub-millimetre accurate computer-controlled platform, a mechanical finger, Flat Digital Foam input device and a software application to perform monitoring of both the Digital Foam data and the mechanical finger's position.

Rather than build a custom computer-controlled platform, a commercially available TAIG Computer Numeric Controlled (CNC) mill was selected for its availability and because it provides a platform capable of precise movements required for the repeated stroke operation. The Flat Digital Foam prototype is securely fastened to the bed of the platform and can also be seen in Figure 6.1(a). The Digital Foam's working area is 200mm (X axis) $\times$ 200mm (Y axis) $\times$ 12mm (Z axis), and the computer-controlled mechanical finger allows 200mm motion on the X axis, 130mm on the Y axis and 12mm on the Z axis. The limited motion on the Y axis is a physical limitation of the computer-controlled platform and is not expected to cause any significant problems for the experimental procedures.

The mechanical finger was constructed and installed to the computer-controlled platform



(a) (b)

Figure 6.1: Experimental apparatus: (a) Apparatus setup with Flat Digital Foam installed below the mechanical finger to allow computer-controlled stroke operations to be performed. (b) Close up of the mechanical finger next to a human finger.

(shown in Figure 6.1(b)). It is used to provide a means of pressing into the Digital Foam surface and perform a stroke operation without damaging the surface. Both the rounded edges and smooth finish ensured this functionality. It is constructed from a solid bar of 6061 grade aluminium, with a diameter of 18mm and a rounded end to approximate the size of a large human finger. There is no electrical connection between the mechanical finger and the Digital Foam surface, the white material on the Flat Digital Foam surface provides an insulating layer that avoids additional electrical interference.

6.2.2 Evaluation application

In order to control the position of the mechanical finger and log data, an application was written to control the following properties:

- Position the mechanical finger.
- Log the position of the mechanical finger
- Log the reported position of the touch point on the Digital Foam

Configuring the stroke path of the mechanical finger is achieved using a series G-Code commands interpreted by ArtSoft's Mach3[2] commercially-available software application. This software application is run on a dedicated personal computer and allows a configurable stroke path to be easily entered and altered depending on the desired path. Mach3 was also configured with a custom script (provided in Appendix C.3) to send the current X,Y,Z

[2] http://www.machsupport.com/

Name	Type	Bytes	Description
TIMESTAMP	integer	8	The time in seconds when the data sample was taken.
X1	integer	4	Mechanical finger X position in millimeters.
Y1	integer	4	Mechanical finger Y position in millimeters.
Z1	integer	4	Mechanical finger Z position in millimeters.
X2	integer	4	Digital Foam X position in millimeters.
Y2	integer	4	Digital Foam Y position in millimeters.
Z2	integer	4	Digital Foam Z position in millimeters.

Table 6.2: Packet Format ([TIMESTAMP] [X1] [Y1] [Z1] [X2] [Y2] [Z2]) describing each value stored per record.

position information to the RS-232 serial port. A second computer system is used to perform data logging and Digital Foam algorithms. An RS-232 serial connection is made between the computer-controlled platform and the second computer system so the current position of the mechanical finger can be logged in real-time. An RS-232 serial connection is also made between the Digital Foam and the second computer system to allow the execution of algorithms and data logging of the reported position of the digital foam. Each record entered into the log file has the timestamp and position information as described in 6.2. A summary of the communications architecture is provided in Figure 6.2.

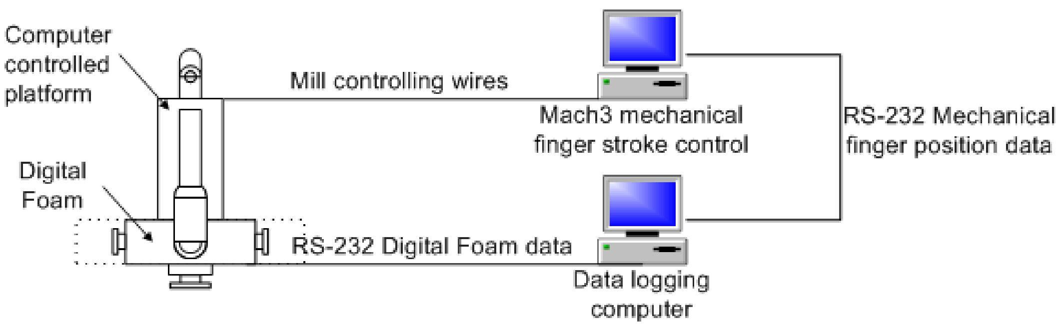


Figure 6.2: Apparatus communications architecture allowing computer controlled platform and data logging control.

6.3 Hypotheses

The following scientific hypotheses are presented and challenged in this evaluation:

- *Hypothesis 1* Predictable output can be obtained from a Digital Foam input device using conductive foam sensors.
- *Hypothesis 2* Applying the 3D cursor tracking algorithm, Digital Foam's performance can be improved to provide more fine-grained control than the physical spacing of each sensor.

6.4 Experiment 1 - Digital Foam benchmark performance

6.4.1 Purpose

The purpose of this experiment is to firstly verify the operating performance of the experimental apparatus, and secondly to capture a benchmark performance of the Flat Digital Foam input device using the unprocessed data. To achieve this, the mechanical finger is configured to make a repeated stroke operation in a straight path along the Digital Foam surface while logging the data.

6.4.2 Procedure

Prior to performing this experiment, the mechanical finger is configured to perform ten identical stroke operations following along the Flat Digital Foam surface. The travelling speed is set to 600mm per minute, for a 160mm long stroke at a depth of 8mm. Figure 6.3 depicts the path the mechanical finger takes for each stroke. Each explicit step is described in the following list (see Appendix C.1 for the full G-code script):

- Step 1: Starting position of the mechanical finger (X=-1.0mm, Y=90.00mm, Z=10.00mm).
- Step 2: Move the finger down into the foam surface (Z=-8 mm).
- Step 3: Slide the finger across the surface: (X=160.0mm).
- Step 4: Move the finger so as it is not touching the Digital Foam surface (Z=10.0mm).
- Step 5: Return to the original location (X=0.0mm).

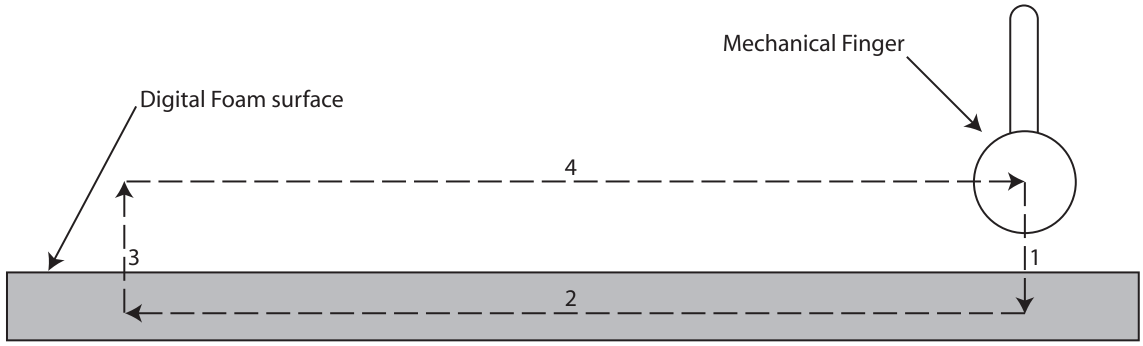


Figure 6.3: Side view of the mechanical finger stroke path.

For each stroke performed when the mechanical finger is in contact with the Digital Foam surface (Stage 2 of Figure 6.3), the current position of both the mechanical finger and the detected position of the Digital Foam sensor is recorded. During this period, ten samples per second are recorded with a unique time-stamp for each record. During the procedure, the raw foam sensor data is used to calculate the location of the mechanical finger on the Digital Foam's surface (discussed in Chapter 5 Section5.2.1). The combination of these three values makes up the detected depression location, and is logged as the detected position on the Digital Foam's surface. The values are recorded as X2,Y2 and Z2 as described above in Equation 6.2.

6.4.3 Results

The total duration of the procedure was 5 minutes and 16 seconds. Each individual stroke performed had a length of 31 seconds, and the mechanical finger was in physical contact with the Digital Foam surface for 16 seconds per stroke. To visualise the data captured, three separate graphs are provided.

The first graph shown provides a top down two-dimensional view showing the X-Y axis, since a straight path was configured as the stroke operation the corresponding path can be seen in Figure 6.5(a). To visualise the depth information a second graph, shown in Figure 6.5(b), provides a front-view displaying the X-Z axis.

Through observation, it was noticed that the diameter of the mechanical finger effects the perceived performance of the Digital Foam surface. It is important to select the finger size carefully to optimise the performance of the 3D cursor tracking algorithm. For example, in this experiment the mechanical finger diameter is 18mm and the physical spacing of the individual sensors on the Digital Foam surface is also 18mm. During operation, it is possible for the mechanical finger to only activate one foam sensor as highlighted in Figure 6.4.3. This observation can be described as a relation between the sensor density and the diameter of the mechanical finger, or more generically the size of the desired minimum touch point. This is an important contributing factor for future experiments, because if multiple sensors are not depressed the interpolation algorithm does not provide additional tracking precision. It was expected that Figure 6.5(a) would have Y values that vary, however due to the relationship between the mechanical finger size and the sensor density there is no variation. The disadvantage of this operation is that verifying the 3D cursor tracking algorithm will not show the benefits that can be achieved.

This experiment has highlighted that the current apparatus configuration is not suitable for testing the 3D cursor tracking algorithm. I have learned from the data captured that the current configuration is not optimal and identified two possible alterations that can be made to improve the evaluation configuration. The first solution would be to build another prototype with a greater sensor density. A terminal spacing of 9mm would allow the 18mm finger to depress two foam sensors when placed in the middle. However, an alternate solution, with much less overhead, is to increase the diameter of the mechanical finger to the required 36mm. An new mechanical finger is easily constructed and will allow the following experiments to be performed employing an optimized design and will allow verification of the 3D cursor tracking algorithm. For future prototype designs this suggests that a spacing of 9mm or less would be more suitable to capture finger based interactions with a higher accuracy.

Given this significant configuration change, the benchmark performance captured in this experiment is not suitable for comparison and must be recaptured with the evaluation apparatus modifications in Experiment 2.

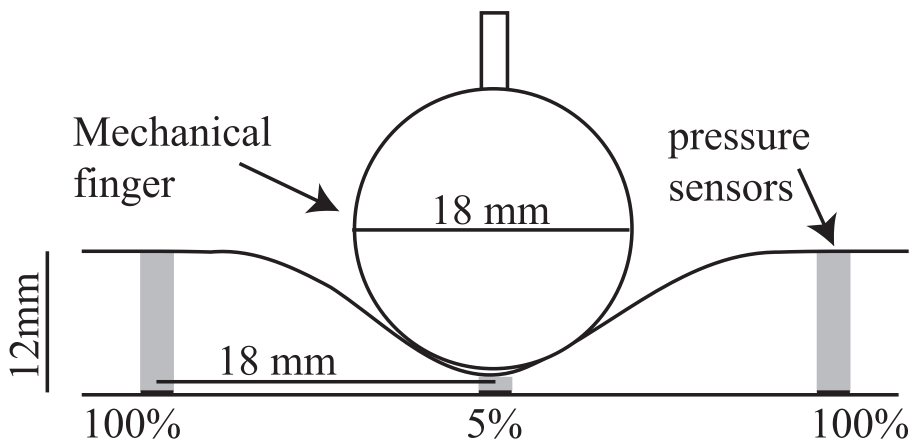


Figure 6.4: Sensor density versus touch point size shows that the touch point size determines if multiple sensors are activated simultaneously.

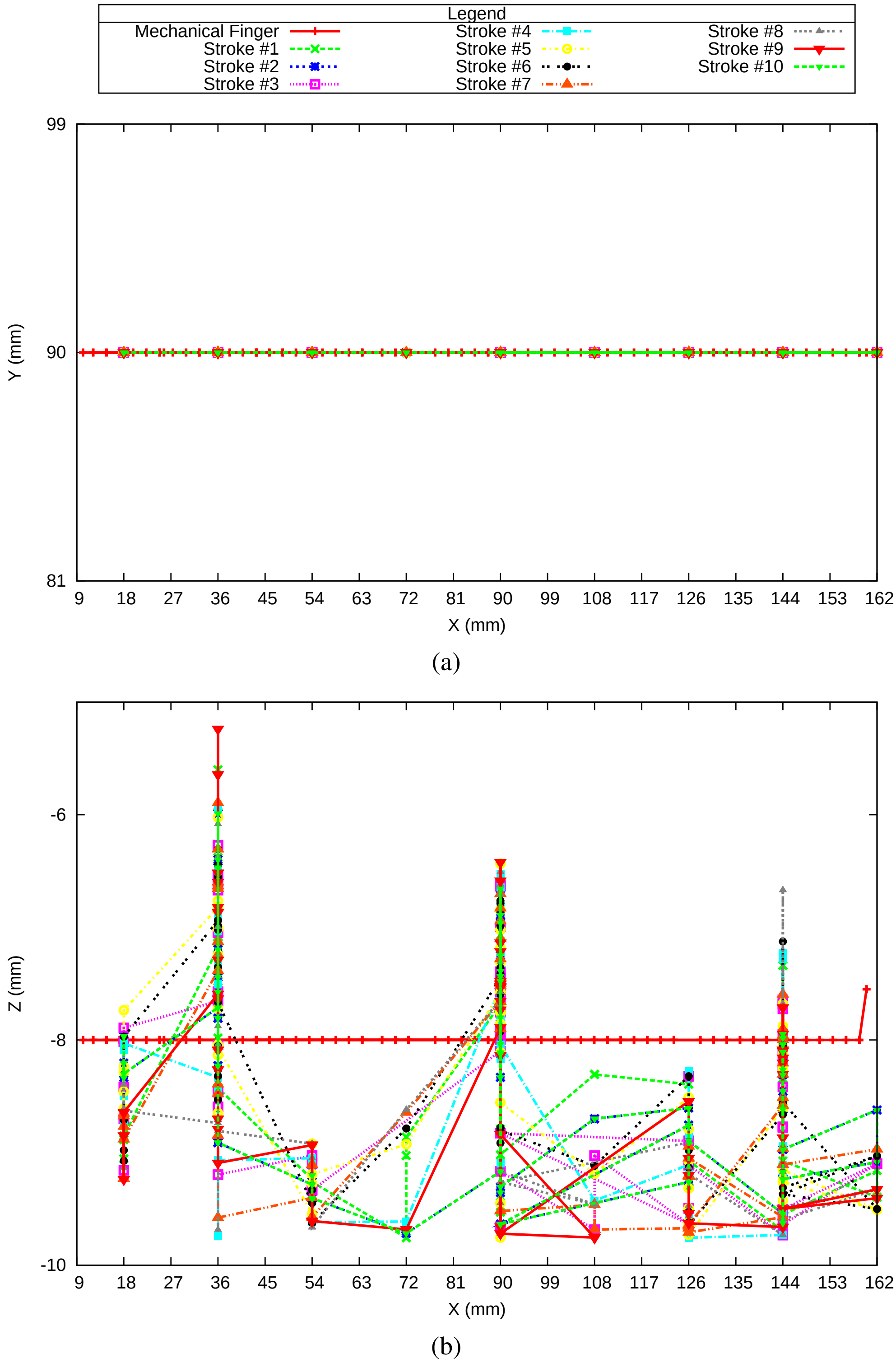


Figure 6.5: Experiment 1 - (a) Showing the raw sensor data of the Flat Digital Foam tablet viewed from the top-down view (X-Y axis). Mechanical finger position is shown with the location of each stroke measured on the Digital Foam surface. (b) Showing the raw sensor data of the Flat Digital Foam tablet viewed from the top-down view (X-Z axis). Mechanical finger position is shown with the location of each stroke measured on the Digital Foam surface.

6.5 Experiment 2 - Simple and complex stroke

6.5.1 Purpose

The purpose of this experiment is to recapture the benchmark data with the modified mechanical finger with a diameter of 36mm (shown in Figure 6.6). Additionally, a new stroke pattern will be performed to further test the transitions between both the X and Y surrounding foam sensors. In total two stroke patterns will be performed, the first one a *simple stroke* (the same as the previous experiment) that follows a straight line and the second a *complex stroke* that follows a path with curves that traverse along multiple sensors on both the X and Y axis. An additional goal of introducing the *complex stroke* is to provide a more challenging and realistic stroke operation that will identify the benefit of the 3D cursor tracking algorithm when applied in the following experiment. Both the data sets produced in this experiment will be used in the third experiment to provide a comparison between the tracked location performance of Digital Foam's raw data compared to data calculated using the 3D cursor tracking algorithm.

6.5.2 Procedure

The procedures used in this experiment are similar as Experiment 1, with the addition of the complex stroke pattern that follows four oval shape arcs. Figure 6.7 depicts a top-down view of the path the mechanical finger will follow. The full G-code listing is provided in Appendix C.2. Additionally, for a more comprehensive data set, the number of strokes performed was increased to forty for both the simple and complex stroke, this was chosen based on an estimated 30minute running time.

Figure 6.6: Mechanical finger modified to a 36mm diameter

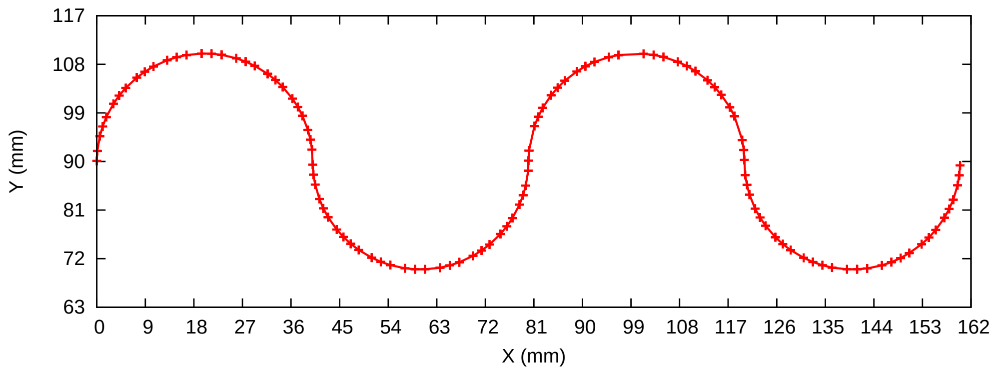


Figure 6.7: Complex stroke path shown from a top-down view, with start and finish displayed

6.5.3 Results

6.5.3.1 Simple stroke

The total duration of the simple procedure was 24 minutes and 25 seconds. Each individual stroke performed took 31 seconds to complete, and the mechanical finger was in physical contact with the Digital Foam surface for 16 seconds per stroke. To visualise the data captured, three separate graphs are provided to assist with describing different aspects of the data.

The first graph shown in Figure 6.8(a) provides a top down two-dimensional view showing the X-Y axis. The discrete sensor locations can be easily identified since their spacing is 18mm apart from each other. Also in this graph it can be noted that the Y value has moved between the fourth, fifth and sixth rows. This is a positive indication that increasing the size of the mechanical finger is causing depressions of multiple pressure sensors when in contact with the Digital Foam surface. With this achieved, the setup configuration is suitable for the benchmark performance capture. To visualise the depth information, Figure 6.8(b) provides a front view displaying the X-Z axis allowing the depth readings of all 40 strokes to be seen. A different colour is used for each stroke recorded, the purpose of these graphs is to provide an overall visualisation of the tracking resolution (The purpose is not to identify each individual stroke as discussed in Experiment 3 discussion).

Visually analysing Figure 6.8(a), the physical location of each sensor can be identified. This observation is based on the grouping of tracked points that each occur at 18mm intervals along both the X and Y axis. Each of these points corresponds with a single foam sensor. The Z value is not constrained by the same 18mm spacing, rather it provides a value between 0-1023 over a 12mm length. This can be identified in Figure 6.8(b); there is a large range of different Z values with a variation less than 18mm between each. The 18mm spacing that occurs in Figure 6.8(a) is of particular interest, as it identifies the physical resolution limit

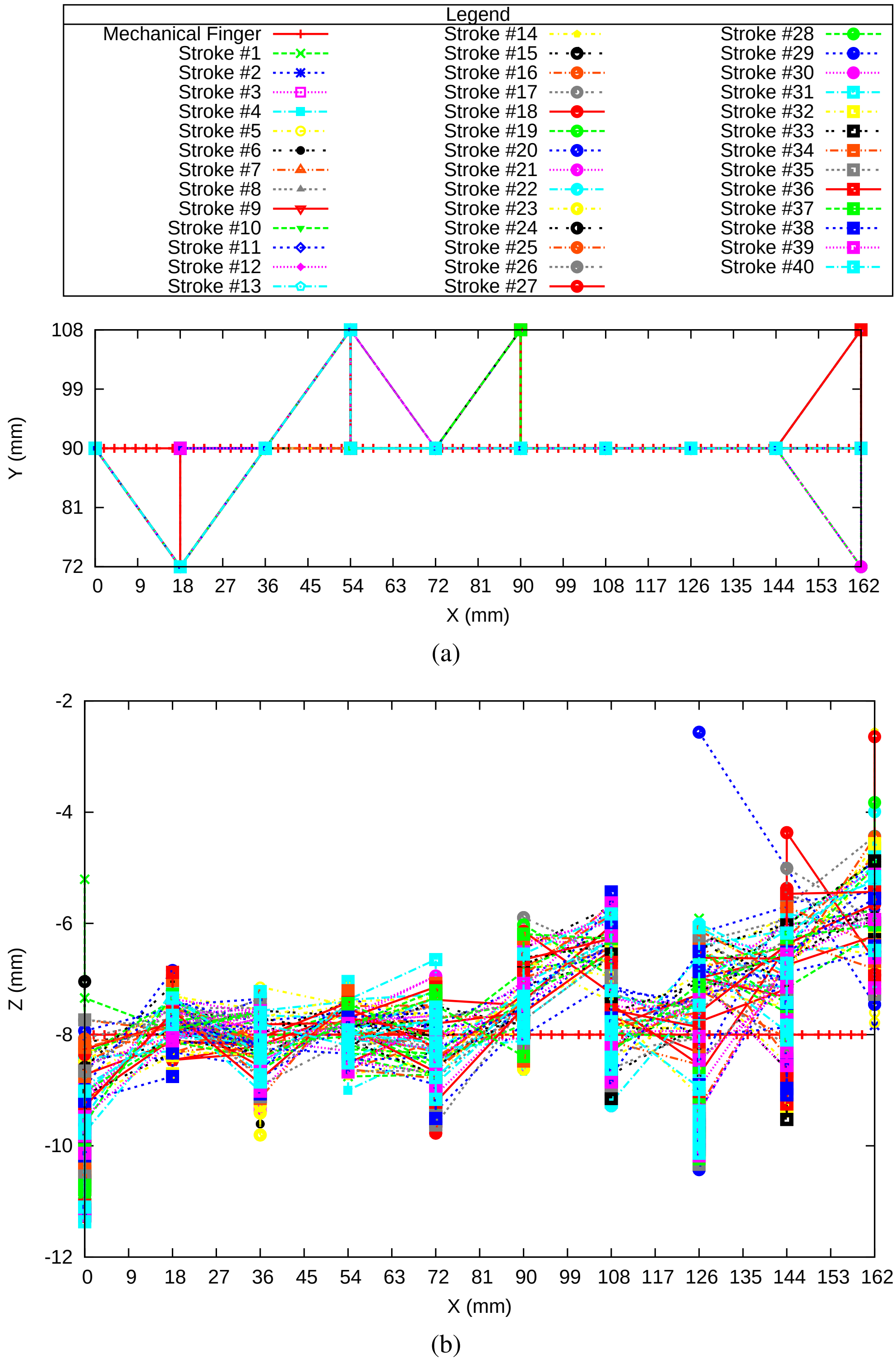


Figure 6.8: Experiment 2 simple stroke - (a) Baseline performance with 36mm mechanical finger along the X-Y axis. (b) Baseline performance with 36mm mechanical finger along the X-Z axis.

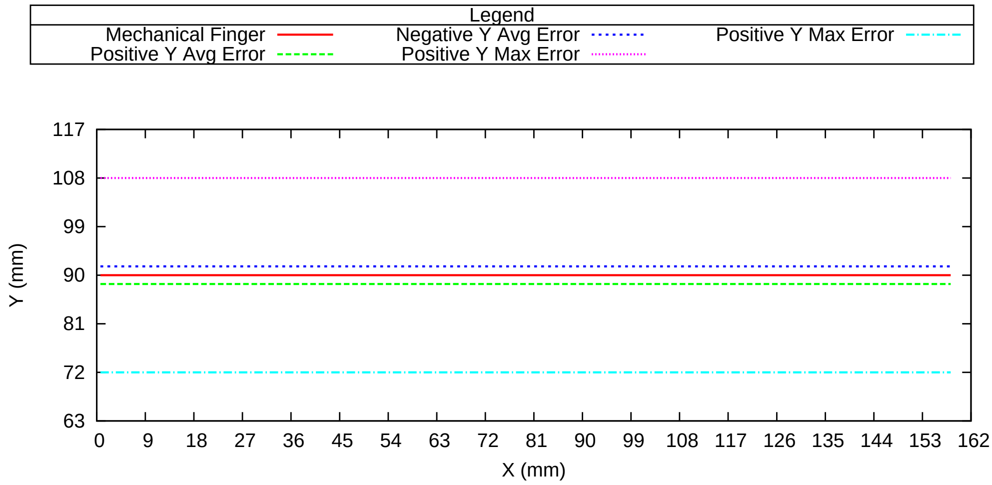


Figure 6.9: Experiment 2 simple stroke - maximum and average error displayed relative to the mechanical finger path.

when using the deepest depression point to identify the X and Y coordinates.

The average error over all 40 strokes was calculated for each axis separately; the X axis 5.56mm (Std. dev.=4.16mm), the Y axis 1.63mm (Std. dev.=5.16mm) and the Z axis 0.727mm (Std. dev.=.67mm). To assist in visualising this data, Figure 6.9 shows the position error of the Y axis. The series line labeled "Mechanical Finger" displays the actual path of the mechanical finger. Immediately either side of this the average error of 1.63mm is shown. The maximum error of 18mm (the physical sensor spacing) is shown on the outermost series lines (labeled Max Error). Each of the stroke operations will be presented in the same format, this will allow a visual comparison of the performance to be performed.

6.5.3.2 Complex stroke

The total duration of the simple procedure was 35 minutes and 29 seconds. Each individual stroke performed took 45 seconds to complete, and the mechanical finger was in physical contact with the Digital Foam surface for 29 seconds per stroke. To visualise the data captured, three separate graphs are provided to assist with describing different aspects of the data.

The first graph shown in Figure 6.10(a) provides a top-down two-dimensional view showing the X-Y axis. The red line indicates the actual path of the mechanical finger while the remaining plots indicate the detected deepest depression path of all 40 passes. This can be seen over both axes much more clearly compared to the previous simple stroke experiments. This highlights the difference in resolution achieved on the Digital Foam surface in comparison to the mechanical finger. The Digital Foam has a 18mm transition between physical sensors while the mechanical finger is sub-millimetre accurate. A depth capture of the X-Z axis is also provided in Figure 6.10(b) with results that provide the same information as the simple stroke.

The average error for the 40 complex strokes was also calculated; the X axis 6.69mm (Std. dev.=5.06mm), the Y axis 8.12mm (Std. dev.=7.4mm) and the Z axis 1.27mm (Std. dev.=.90mm). In comparison to the simple stroke, the error of the X and Y axis values are similar. This is because the complex stroke moves evenly across both the X and Y axis. Figure 6.11 shows the Y axis error to provide a means of visually inspecting the average error of 8.12mm.

6.5.3.3 Discussion

Both the simple stroke and complex stroke benchmark performance have been successfully established in Experiment 2. Analysing the simple stroke operation, it can be observed that there is a distribution of the deepest depression sensor on both the X and Y axis (as can be seen in Figure 6.8(a). The alterations to the size of the mechanical finger successfully caused depressions of multiple pressure sensors simultaneously and will help optimise the performance of the 3D cursor tracking algorithm in the following experiment. Considering the data gathered for the complex stroke, the pattern of the curves can be identified through visual inspection of Figure 6.10(a) although with this tracking algorithm the sensor reduces the resolution of the tracking to 18mm intervals.

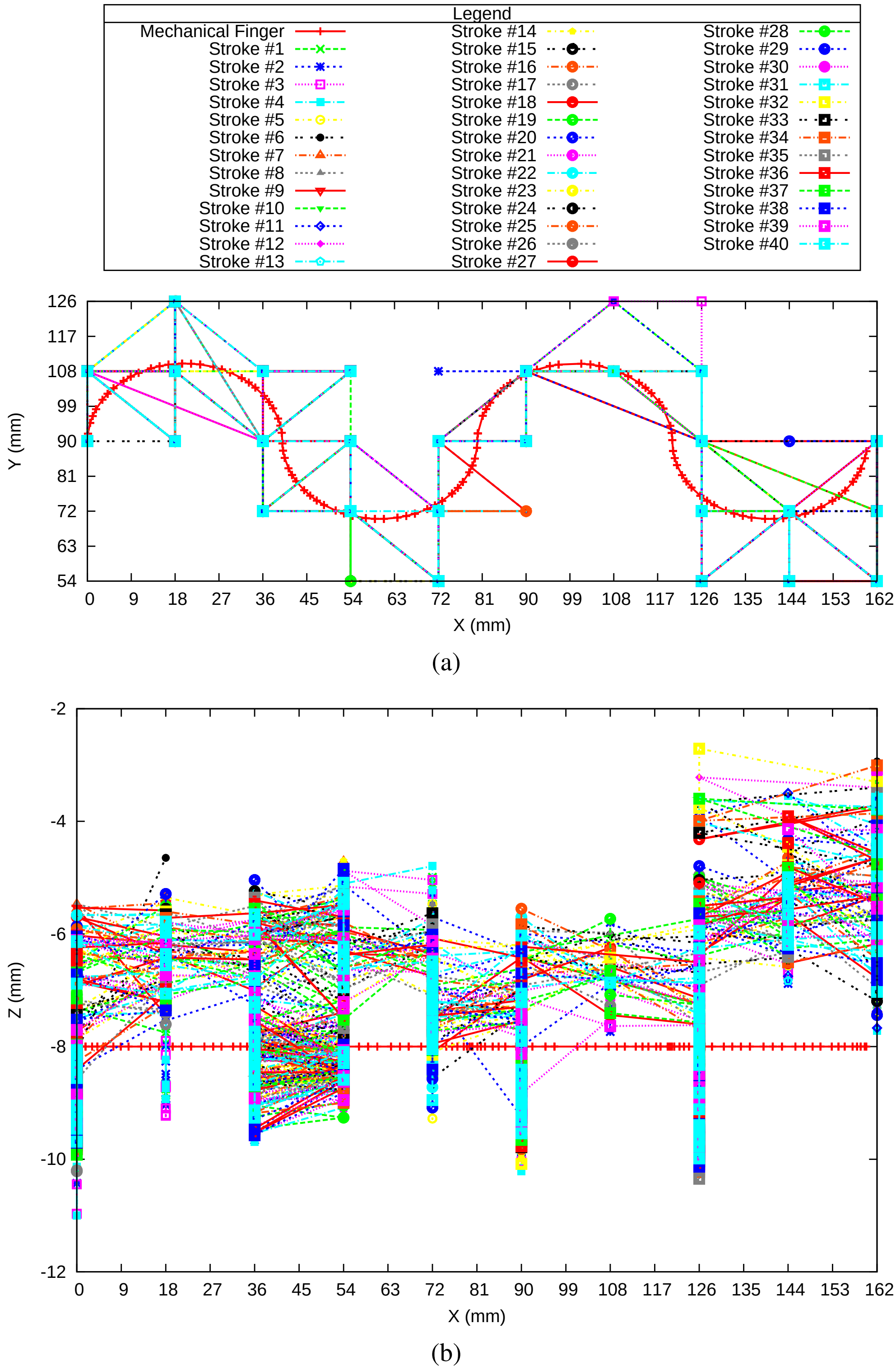


Figure 6.10: Experiment 2 complex stroke - (a) Displaying the benchmark performance with 36mm mechanical finger along the X-Y axis. (b) Displaying the benchmark performance with 36mm mechanical finger along the X-Z axis.

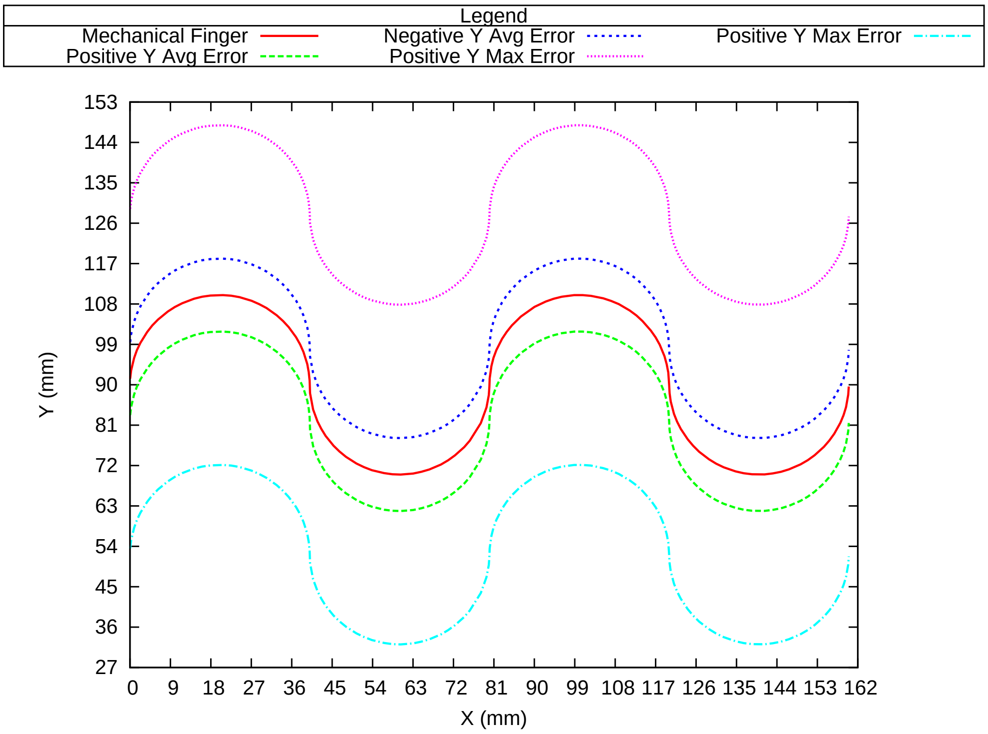


Figure 6.11: Experiment 2 complex stroke - average and maximum error values of the Y axis with the actual path of the mechanical finger shown in red.

6.6 Experiment 3 - Interpolation algorithm

6.6.1 Purpose

The purpose of this Experiment is to test *hypothesis 2*, stating that an improved position accuracy can be gained by combining the surrounding pressure readings of a single touch point on the Digital Foam surface. The surrounding sensor readings are combined using the 3D cursor tracking algorithm as described in Chapter 5 Section 5.2.1).

6.6.2 Procedure

Both a simple stroke and a complex stroke will be performed as described in Experiment 2 with the 3D cursor tracking algorithm applied to the raw sensor data from the Digital Foam surface. The raw sensor data will use the additional algorithm shown in Equation 6.1 (previously discussed in Chapter 5 Section 5.2.1).

$$CP = s_5 + \sum_{i=1}^{9}(d_i * |sp_i|) \tag{6.1}$$

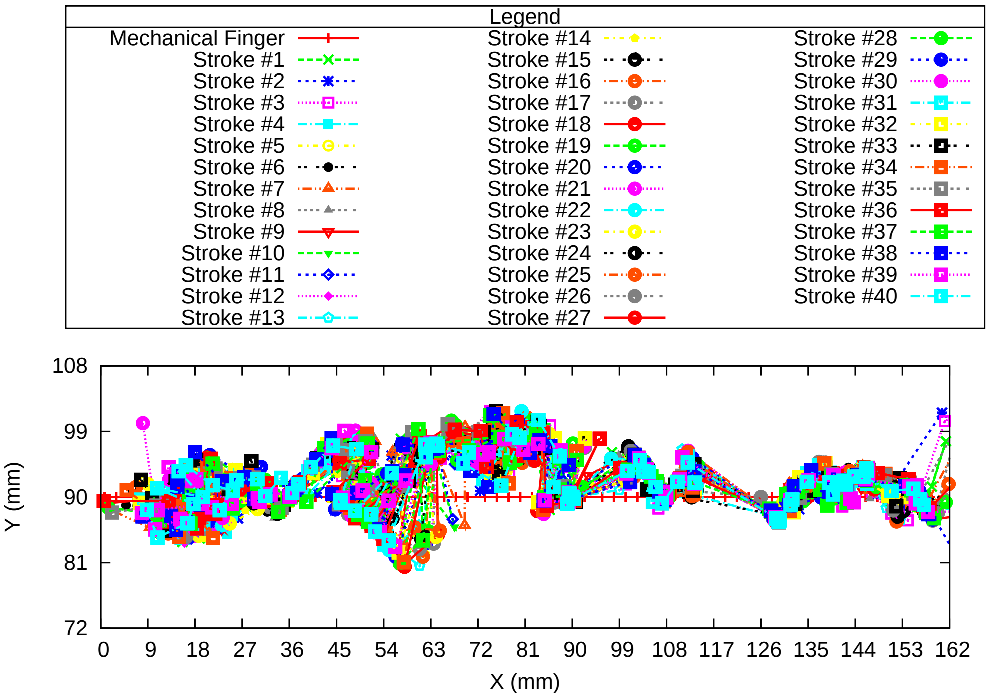
CP = cursor location.
d_i = Direction vector pointing towards s_i from s_5.
sp_i = Normalized pressure sensor reading.

6.6.3 Results

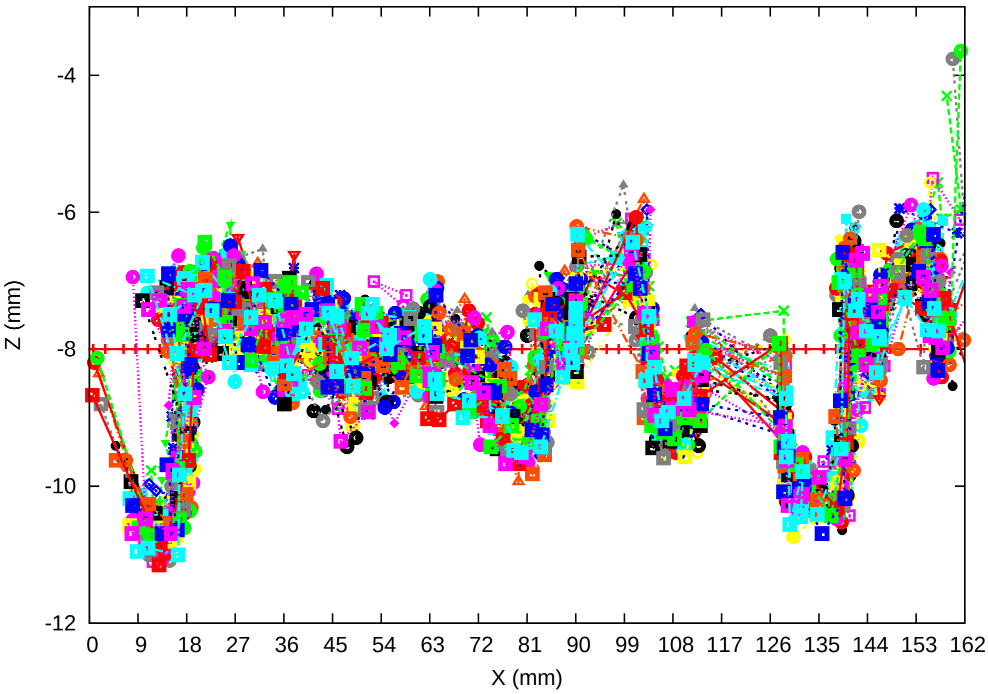
6.6.3.1 Simple stroke

The total duration of the simple procedure was 21 minutes and 20 seconds. Each individual stroke performed took approximately 31 seconds to complete, and the mechanical finger was in physical contact with the Digital Foam surface for 15 seconds per stroke. To visualise the data captured, three separate graphs are provided to assist with describing different aspects of the data.

Figure 6.12(a) provides a top down two-dimensional view showing the X-Y axis. To visualise the depth information, Figure 6.12(b) provides a front-view displaying the X-Z axis. Visually comparing data from Figure 6.8(a) to Figure 6.12(a), a significant difference in the tracked location can be seen. Figure 6.12(a) is using the algorithm to improve the location based on the surrounding pressure sensors. An analysis of the stroke data gathered shows the average error of each of the axis as follows: the X axis 4.04mm(Std. dev.=3.12mm), Y



(a)



(b)

Figure 6.12: Experiment 3 simple stroke - (a) Using 3D cursor tracking algorithm with 36mm mechanical finger along X-Y. (b) Using 3D cursor tracking algorithm with 36mm mechanical finger along X-Z. Note: The large sample rate taken during this experiment makes the points appear cluttered, the following graph (Figure 6.13) provides a summary of the average error rates with a reduced sample rate.

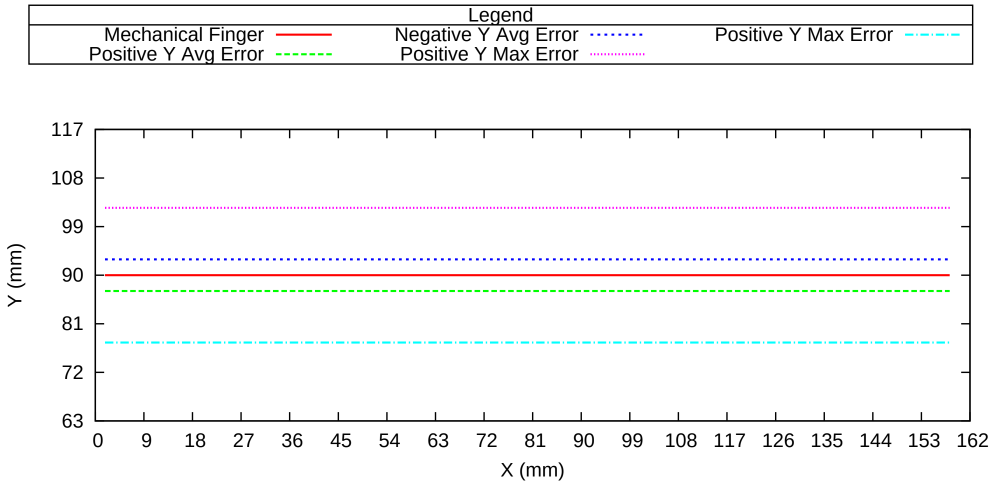


Figure 6.13: Experiment 3 simple stroke - maximum and average error displayed relative to the mechanical finger path.

axis 2.94mm (Std. dev.=2.54mm) and the Z axis 0.75mm (Std. dev.=.66mm). In comparison to the previously gathered benchmark data from Experiment 2, the average X axis error has reduced from 5.56mm to 4.04mm. While the Y axis has shown an increased error (1.63mm to 2.94mm), the simple stroke moved along a fixed Y axis meaning it was not optimally tested. However a more optimal test is done in the following section with the complex stroke. Figure 6.13 shows the path of the mechanical finger in the middle with the red series line, while the average Y error and maximum error are shown either side. The Z axis error increased from 0.72mm to 0.75mm. It was expected that the Z axis performance would not change since its location is measured directly on the foam pressure reading, unlike the X and Y that use the known physical location to estimate the position.

6.6.3.2 Complex stroke

The total duration of the complex stroke procedure was 38 minutes and 24 seconds. Each individual stroke performed took approximately 45 seconds to complete, and the mechanical finger was in physical contact with the Digital Foam surface for approximately 29 seconds per stroke. To visualise the data captured, three separate graphs are provided (see Figure 6.14(a), Figure 6.14(b) and Figure 6.15) to assist with describing different aspects of the data.

The first graph shown in Figure 6.14(a) provides a top-down view showing the X-Y axis. This graph demonstrates the improved performance achieved using the 3D cursor tracking algorithm. This can be identified by visually comparing Figure 6.10(a) and Figure 6.14(a) that show the tracked point following the mechanical finger, in Figure 6.10(a) the detected touch-point location is very close to the mechanical finger. The results of this experiment show that the average position error was reduced on both the X and Y axis, from 6.69mm to 4.55mm and 8.12mm to 3.83mm respectively.

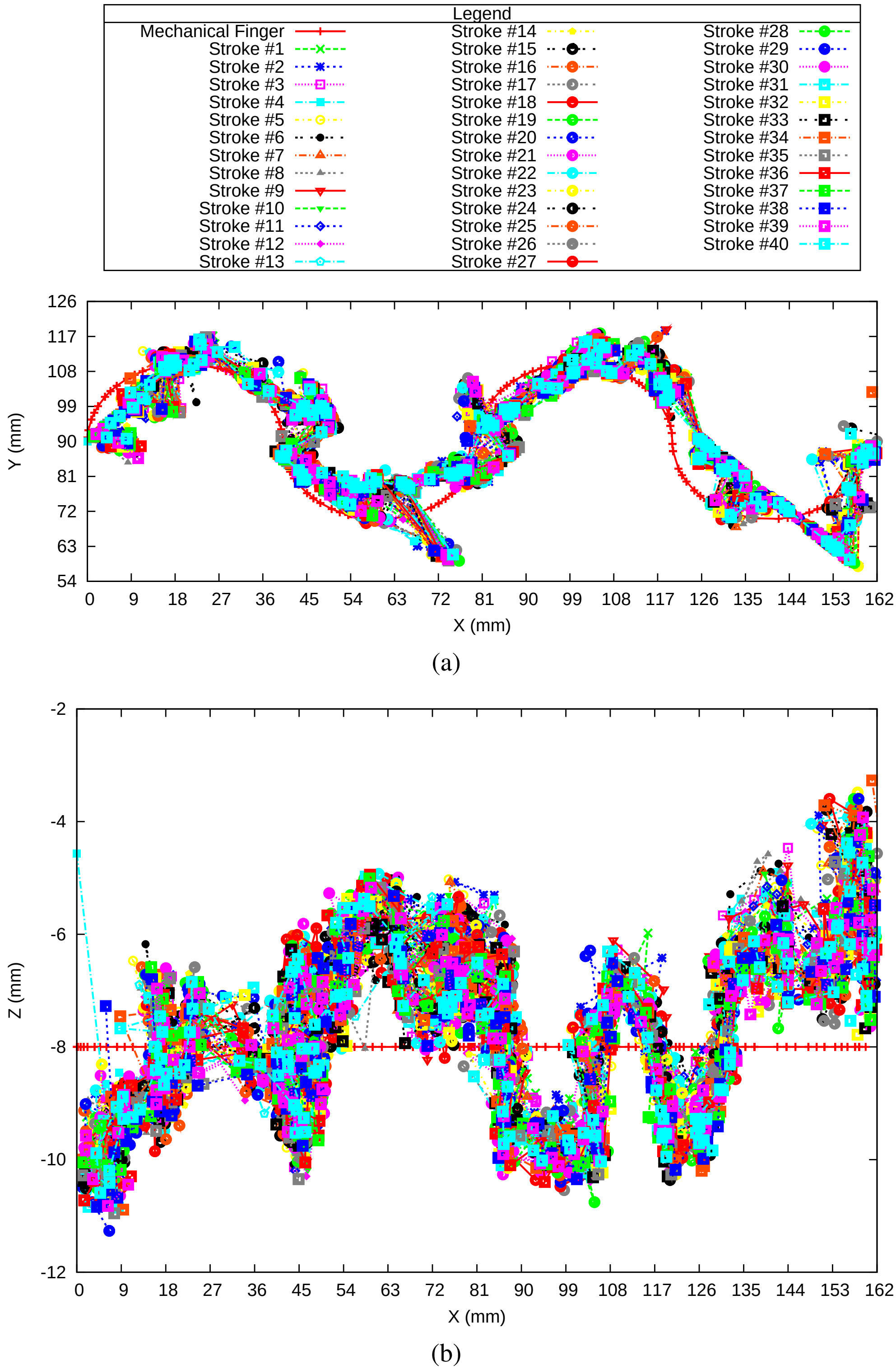


Figure 6.14: Experiment 3 complex stroke - (a) Complex stroke performance using cursor tracking algorithm with 36mm mechanical finger along the X-Y axis. (b) Complex stroke performance using cursor tracking algorithm with 36mm mechanical finger along the X-Z axis. Note: The large sample rate taken during this experiment makes the points appear cluttered, the following graph (Figure 6.15) provides a summary of the average error rates with a reduced sample rate.

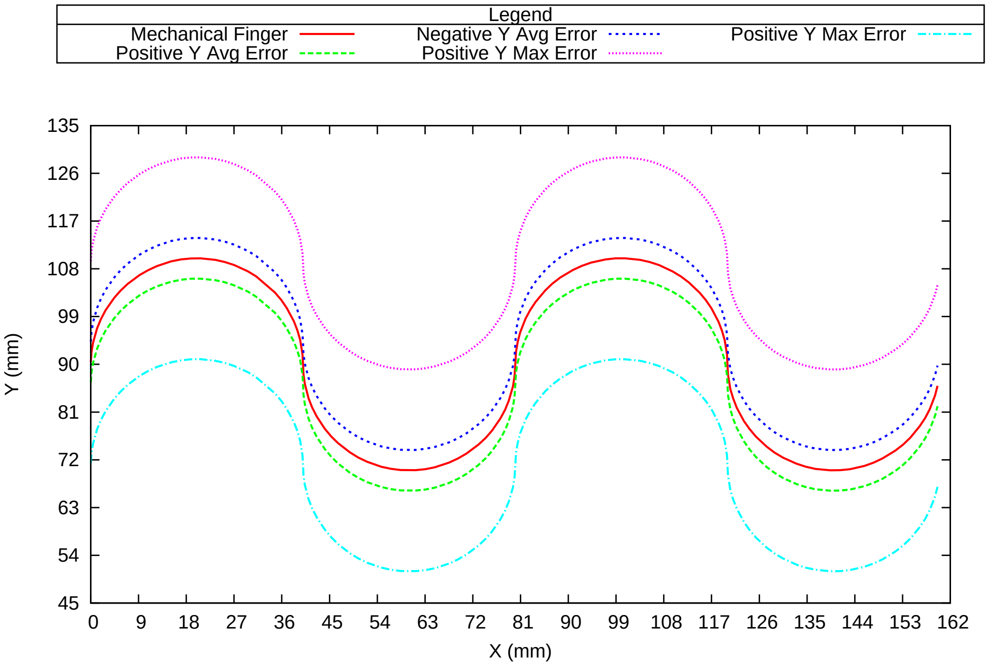


Figure 6.15: Experiment 3 complex stroke - average and maximum error values of the Y axis with the actual path of the mechanical finger shown in red.

6.7 Trial user study

A trial user study was conducted to gather qualitative user experience information when using a Spherical Digital Foam input device to control a menu system. Five participants took part in the study, 4 male and 1 female with ages from 20 to 29. Each subject was asked to use a Spherical Digital Foam input device to navigate through five separate menu options.

The experiment was conducted in the following order: The input device was described and subjects were given time to familiarize themselves with the Spherical Digital Foam menu interface. The menu was configured to have five menu items (red, green, blue, black and white) each of which change the colour of a large sphere in the centre of the screen. Each subject was then asked to perform two tasks. First, participants were invited to hold the Spherical Digital Foam with one hand to select an ordered series of options from the menu. For the second task, the menu system maintained the same configuration and participants were asked to hold the Spherical Digital Foam input device with two hands and select another ordered series of menu options. Once completed, subjects were asked to fill in a questionnaire with 9 questions (shown in Table 6.3) with a Likert scale from 1 - 5, where 1 indicates "very easy, too small, strongly agree" and 5 indicates "very hard, too large, strongly disagree".

The results of this study provided valuable feedback for the future Digital Foam design parameters. Due to the shielded design of Digital Foam's conductive fabric material (described [SMIT08b]), the Inertia Cube's magnetometer experiences a weaker than normal magnetic field from the Earth, causing the orientation tracking to drift over time. This technical problem made menu selection more difficult. When selecting menu items, drifting orientation values occasionally caused the incorrect item to be selected.

If this occurred the instant before a click event, an incorrect menu item would be selected. One user suggested not accepting the click event if the menu item had only been highlighted for very short time. Although the drift affected the accuracy of selecting options, when asked if the rotation angle to transition between menu options was too small or too large (Table 6.3 Q5) both the average response (3.6) and user comments indicated a smaller transition angle is desirable. This highlights the importance of the orientation tracking resolution, and the goal should be to improve this in future iterations of the hardware. As expected, another feature reliant on orientation tracking is the up-side-down menu entering technique, users operation of this technique appeared unaffected by the orientation drift. All subjects indicated that it was very easy to enter the menu mode by turning the Spherical Digital Foam input device up-side-down (Table 6.3 Q1). We note the importance of tracker resolution directly affects how well a user can control the desired operations.

The 11cm diameter of the Spherical Digital Foam input device is a characteristic that

Question	Average	Std. dev.
Q1: Displaying (turning on) the menu was:	1.0	0.00
Q2: Performing a click using Digital Foam:	3.4	0.54
Q3: Selecting the correct menu item was:	3.8	0.83
Q4: I found the input device:	3.4	0.89
Q5: The rotation angle to change menu items was:	3.6	1.67
Q6: I found operating menus with one hand:	3.8	1.30
Q7: I found operating menus with two hands:	1.8	0.83
Q8: Overall I found the menu easy to use:	3.0	1.00
Q9: Overall I could control the menu system:	2.0	1.22

Table 6.3: Digital Foam menu user evaluation questions - Response options with a Likert scale from 1 to 5 where 1 = Very Easy or Too Small or Strongly Agree and 5 = Very Hard or Too Large or Strongly Disagree.

may be optimised. When asked if the input device was too small or too large (Table 6.3 Q4), the average (3.4) and user comments indicated a smaller size would be more comfortable and easier to use. The comfort of an input device is important, and the Spherical Digital Foam device is designed to be hand held, but the current size is not optimal. A suggestion for future designs is to reference the size of juggling balls commonly used by street performers. Common sizes range from 5cm to 10cm and could be used as a benchmark for future development characteristics.

All subjects indicated that operating the menu with one hand was difficult in comparison to using two hands (Table 6.3 Q6 and Q7). It was observed that while using two hands, users would shuffle the input device while scrolling through menu options. However, when using one hand this is a difficult operation. Altering the menus up-side-down entering operation, to perhaps a partial rotation, and reducing the transition angle for menu item transitions may improve the performance for single handed operation, although this is not a currently significant requirement.

6.8 Summary

The first section of this chapter presented an evaluation of the Digital Foam sensor to record a benchmark performance of two stroke operations. A number of interesting aspects of the Digital Foam's performance have been observed based on the three experiments presented. Firstly, the size of the object causing the depression on the foam surface, as well as the physical sensor density is critical for this algorithm to perform well. Experiment 1 and the results shown in Figure 6.5(a) highlight this, where the Y axis information did not deviate to the surrounding sensor rows, yet it was expected that there would be some deviations. After analysing the setup, it was found that the mechanical finger was not causing any depression on the surrounding Y axis sensors. This limitation was corrected for Experiment 2 by increasing the mechanical finger size to 36mm. The effects of this change can be seen in the results of Figure 6.8(a), where the Y axis values move between both surrounding rows on the Y axis during a simple stroke.

With the alterations made to the computer controlled mechanical finger, the results from Experiment 2 provided a benchmark performance for both a simple and a complex stroke. A goal of this experiment was to test *hypothesis 1:* “Predictable output can be obtained from a Digital Foam input device using conductive foam sensors”. The combined experiments have demonstrated this to be true. For the general case, the average error (X=4.55mm, Y=3.83mm, Z=1.26mm) can be used to predict what zone a touch-point occurs within. While the maximum error values recorded (X=14.98mm, Y=19.02mm, Z=5.36mm) can be used at the worst case scenario.

The second goal of this experiment has been to test *hypothesis 2:* “Applying the 3D cursor tracking algorithm, Digital Foam’s performance can be improved to provide more fine-grained control than the physical spacing of each sensor”. This was based on the assumption that when a touch-point on the Digital Foam’s surface causes a depression, a group of sensors will register the deformation and can all be combined to calculate a location in 3D space with an accuracy that exceeds the spacing between each physical sensor. This was demonstrated to be true as can be seen when comparing the results of Experiment 2 (Figure 6.10(a)) and Experiment 3 (Figure 6.14(a)) where a both the statistical analysis and the visual inspection has shown an improved performance. This improvement is based on the physical response of the foam material and the assumption that a group of foam sensors will be depressed at any one touch-point. It was shown that the average error was reduced along the X axis from 6.69mm to 4.55mm and the Y axis from 8.12mm - 3.83mm showing an improvement in performance when using the tracking algorithm. Figure 6.16 summarises a complex stroke showing the mechanical finger location, Digital Foams raw data, and the cursor tracking algorithm. The data is a summary using a 1mm linear interpolation to show the average of the 40 passes in one series line and provides a visualisation of the performance achieved.

A trial user study was also presented that has evaluated qualitative aspects of the menu system developed for Spherical Digital Foam. The menu system was well received, but a limitation in the sensing of the orientation caused a number of problems with menu item selection. Trial study results have facilitated new prototype, technique and user evaluation design directions.

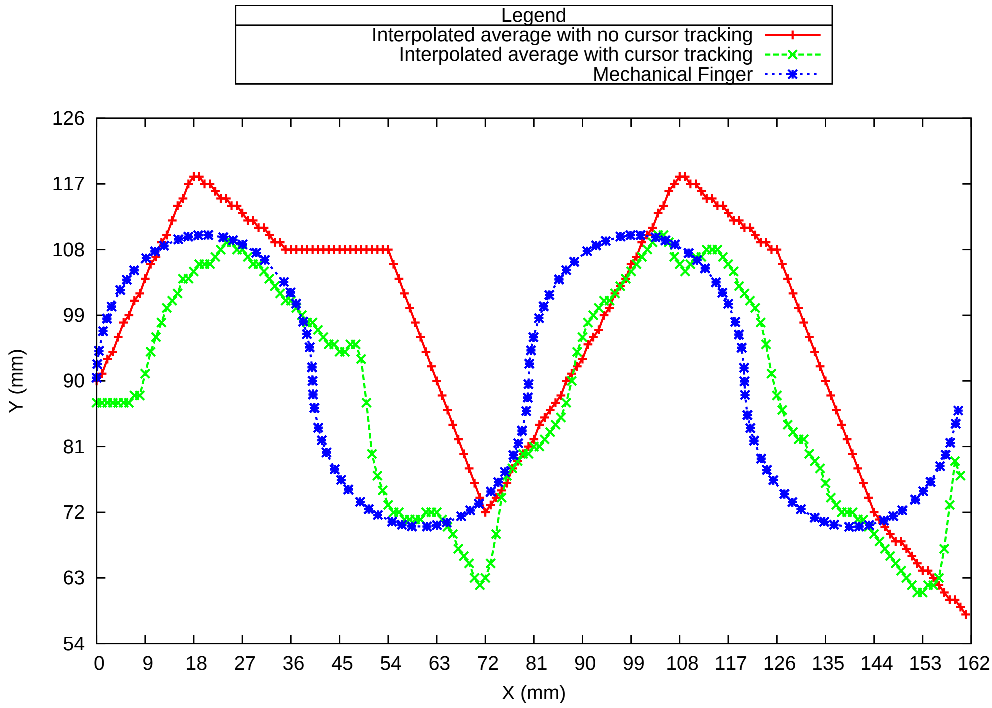


Figure 6.16: Comparison between the actual position of the mechanical finger, the raw Digital Foam data and the cursor tracking algorithm while performing a complex stroke 40 times.

7

Conclusion

This dissertation has presented contributions to the development of deformable input device technologies that facilitate a number of novel human-computer interaction techniques. The contributions can be summarised as the development of the Digital Foam input device, a number of interaction techniques to support sculpting metaphors, a multi-point cursor tracking algorithm for the Digital Foam sensor and an evaluation of the performance of the Digital Foam. These contributions address the research questions and goals raised in the introduction of this dissertation (see Chapter 1 section 1.1.1).

This chapter begins by discussing the research approach taken, followed by describing each of the key contributions in detail. This dissertation is then concluded by discussing the future directions of this research and the commercial potential that has been identified based on the technologies presented.

7.1 Approach

There are a great deal of computer input devices currently available, but the keyboard and mouse are still the most common and generic devices used on personal computers. My approach has not been to find a replacement for these devices, or the WIMP paradigm. Rather, I have explored the physical sculpting of soft materials and investigated how the well developed techniques of this process can be captured, allowing a computer system to provide a similarly engaging and expressive modelling experience. The approach is focused on targeting those interested in creating 3D models and capturing artistic gestures for human-computer interactions.

7.2 Contributions

The five primary research contributions presented in this dissertation are described in the following section.

7.2.1 Sculpting metaphor

Techniques used by material sculpting artists can be captured and applied to the creation and manipulation of 3D virtual models. The work presented in Chapter 3 has identified a number of gestures that are commonly used when sculpting soft materials such as clay or Play-doh®.

A number of benefits of the techniques used when sculpting have been identified based on well known human-computer interaction philosophies. These well established human-computer interaction philosophies support the argument that techniques used when physically sculpting materials are well suited to the creation and manipulation of virtual models. For example, Norman suggests that by carefully designing computer input devices that leverage a user's existing skills, such that the operation of the device is intuitive, this will reduce the training time and operating complexity. Additionally, a significant aspect of the sculpting experience is the feel of the material during sculpting.

Providing similar tactile responses whilst performing virtual sculpting supports a realistic modelling system and further leverages sculpting affordances. By capturing and adopting the techniques used for material sculpting, a computer modelling application provides a similar expressive free-form nature that allows multiple finger and handed gestures to enrich the human-computer modelling interaction experience.

7.2.2 Digital foam sensor

To provide a similar tactile sensation that is experienced when performing sculpting of soft materials, a new deformable interactive surface has been invented and presented as a significant contribution of this dissertation. Digital Foam employs an array of conductive foam sensors to create a novel interactive surface capable of capturing its own geometry in real-time. The construction technique combines both conductive and non-conductive foam materials to produce an interactive multi-touch pressure sensitive surface with a unique tactile response.

Four separate prototypes that employ Digital Foam as the primary sensor to capture physical world input have been presented. There are two primary physical design layouts, Flat Digital Foam and Spherical Digital Foam, that have explored two physical forms of the novel sensor. Flat Digital Foam is a planar surface that can be used as a tablet-like input device or table-top surface allowing multiple users to interact with the surface simultaneously. Spherical Digital Foam is designed as a task specific device to support virtual sculpting without the assistance of additional input devices such as a keyboard or mouse. The construction techniques employed to build each of the prototypes has been presented in detail.

Finally, the university's commercialisation company, ITEK, has recognised Digital Foam as a significant intellectual property and has supported protecting the Digital Foam concept by submitting a US patent with application number: 12/381147 (Attached in Appendix A).

7.2.3 Sculpting interaction techniques

Employing the Spherical Digital Foam device to perform a variety of sculpting and modelling operations required the development of new interaction techniques. Free-form sculpting is the intended operation of Spherical Digital Foam and supports the creation of new models. These models are created by starting with a base shape such as a sphere or a cube, and allowing a user to modify the shape by deforming the surface of the Spherical Digital Foam input device. Existing models can also be modified by performing a mapping between the physical device and the virtual model, as described in Chapter 5 Section 5.1.2.2. Accumulative operations can also be performed using a clutching mechanism, so the size of the virtual model is not restricted to the size of the input device itself. Additionally, the half-hemisphere technique supports intuitive sculpting operations by removing unwanted depressions caused by a user's grip at the back of the sphere device. Common operations such as scale, rotate, load and save have all been demonstrated using the Spherical Digital Foam input device. Finally, to support the operation of a modelling system using Spherical Digital Foam as a sole input device, a new menu system has been developed. Both the internal orientation sensor and the Digital Foam sensor are employed to operate the menu system.

7.2.4 Cursor tracking algorithms

Two algorithms to track the location of a 3D point in space for a pressure sensitive surface are presented. The cursor tracking algorithm exploits the physical property of the Digital Foam material that causes a number of pressure sensors to be depressed around any one touch point. This algorithm provides a tracked location with granularity that is smaller than the physical positioning of the foam sensors, and can be used for a pointing device such as a cursor. The second algorithm presented extends the functionality of the first by allowing multiple locations to be tracked simultaneously whilst maintaining a separate identification number for each. This algorithm has been demonstrated using the Digital Foam surface but could also be employed on other pressure sensitive surfaces that have a similar row and column physical layout.

7.2.5 Evaluation

The focus of the evaluation is to test the 3D cursor tracking algorithm to verify that improved performance is achievable compared to using just the raw sensor data. To perform this evaluation, a custom mechanical finger apparatus was constructed that allows a repeatable stroke to be performed on the Digital Foam surface. This is used to capture the baseline performance of the Digital Foam and also to analyse the improvements gained from the 3D cursor tracking algorithm. The results of the evaluation have shown that the hypothesis "applying the 3D cursor tracking algorithm, Digital Foam's performance can be improved to provide more fine-grained control than the physical spacing of each sensor" is valid. The initial trial study performed gathered user acceptance data for the Spherical Digital Foam input device. This allowed the identification of areas in which hardware advancements should be focused on, and will provide a valuable data for future formal user studies as the technology matures.

7.3 Future developments

Given the new functionality Digital Foam provides, there are a number of directions for future research. Given that using conductive foam as a sensing material is not a regularly employed approach, it is envisaged that there is a lot of room for the advancement of the foam sensor sensor. Additionally, the interest of the Digital Foam sensor for use in a number of domains, such as medical training mannequins, mobile device interactions and game consoles, suggests it is a fruitful area of research. This sub-section presents my personal opinions, and also the suggestions others have made to me, in which I feel provide compelling examples for future work.

7.3.1 Sensor advancements

There is room for advancements to both the electronics and the physical layout of the Digital Foam sensor. The current electronics design uses a microcontroller and analogue-to-digital converters to capture the compression of the conductive foam. This fundamental approach will likely stay the same, however more advanced electronics that provide filtering circuits will likely improve the performance of the sensor. The physical construction can also be improved. A lot of the construction for the prototypes was performed manually using hand tools, which do not provide the precision of computer-controlled machinery.

Improving the accuracy of cutting the holes in the foam materials during construction will also increase the performance. For example, if the size and volume of each sensor is more regular there will be less variation in the length readings of each discrete sensor. Additionally, in future designs the possibility of terminating both the top and bottom of the conductive foam to a unique input/output pin on the microcontroller may lead more advanced geometry capture algorithms using a non-linear scanning approach. In this proposed design, it would be possible to use a single piece of conductive foam material rather than the combined conductive and non-conductive design presented in this dissertation.

7.3.2 Modular design

One interesting direction of future research is to apply the existing Digital Foam technology to develop and create a new modular design with sensor modules that can snap together physically and electronically. This will allow for an arbitrary number of modules to be constructed into different shapes and sizes. Based on the existing prototypes, each snap-together module could be 20cm x 20cm, with all the required electronics embedded in each module. The modules could easily employ a master / slave architecture to support a scalable approach. Conceptually, any surface can be covered with modules, each equipped with its own microcontroller to process the sensor information. The master / slave architecture is well suited to Digital Foam, as it supports the high bandwidth that is required for a large-scale surface as the number of sensors increases.

7.3.3 Actuated design

Another more challenging advancement could incorporate an array of actuators into the foam sensor that are designed to hold the shape of the foam after it has been pressed. In conjunction with projected graphics onto the table's foam surface, this would provide an interactive display area that is capable of allowing 3D visualisations unlike any existing table-top display surface. One of the more difficult construction problems is to fit a large numbers of actuators side by side. Mazzone et al. have presented some initial works on their smart mesh that can actively change its shape in real-time [MAZZ04], these technologies may eventually be combined with Digital Foam to create hybrid surfaces. Additionally, using computer graphics (CG) techniques may be employed to compensate where the number of actuators is reduced, and high-detail graphics are projected onto the table's surface providing the appearance of more complex physical geometries. Well known techniques such as bump mapping give a flat surface a 3D appearance, and in conjunction with shadows and other computer graphics methods the complexity of the appearance will be improved. The overall goal of this advancement is to generate a physically-animated presentation by changing the Digital Foam's shape in addition to the projected visualisation.

7.3.4 Application domains

In this sub-section I briefly describe three compelling future applications. Firstly, a medical training simulator that allows students to feel with their finger tips the skin, underlying tissue, and joints using a mannequin covered with a Digital Foam surface. Existing sensor technologies do not provide a tactile response that is similar to the human body. The Digital Foam sensor itself has a similar feel to a human body and can be manufactured in many different shapes and sizes, providing unique functionality.

Another interesting application for Digital Foam is to use it as a touch surface on a mobile device or a game controller. It may be used in place of a button to provide a miniature touch based surface that can capture simple gestures allowing 3D navigation and manipulation operations.

Finally, investigating a flexible version of Digital Foam that can be employed as a skin material for complex shapes provides a compelling future direction. The initial concept is to replace the rigid PCB material of the Digital Foam with a commercially available flexible PCB material. This would allow the construction of more complex shapes than the current planar or spherical versions. A novel application is to cover the entire surface of a robotic arm with flexible Digital Foam, producing a sensor that is an analogue to human skin. The goal is to create a sense of touch that can be interpreted by a computer-controlled robotic arm. This will enable the robotic arm to sense through touch anything it has collided with an external entity. The location and pressure of the collision may then be used to determine what action should be taken. Reasoning algorithms may be applied and developed specifically for Digital Foam to take advantage of the unique sensor information.

7.4 Epilogue

Digital Foam shows a great deal of promise for use as a new sensing medium, particularly for use with computer input devices. There has been interest expressed in the capabilities of the Digital Foam sensor and how it can be applied to new domain applications since the first publication. This has lead me to believe that pursuing this area of research will be rewarding and continue to contribute to human-computer interaction research. It is my sincere wish that this technology can be developed further to fully exploit the potential made possible using Digital Foam's high-fidelity, deformable interactive surface to facilitate novel human-computer interactions.

A

Digital Foam Patent

The commercialisation company of the University of South Australia, ITEK, expressed particularly interested in Digital Foam and is commercial applications. To protect the intellectual property of the research performed for this dissertation they have both supported and provided resources to patent the significant commercial contributions. The following document describes these aspects in detail and was submitted for a US patent with application number: 12/381147 [SMIT09].

This invention is in the field of haptic sensors and the computer related and assisted functionality which becomes possible with the output from such sensors.

BACKGROUND

Surface modelling and geometry capture are used in a range of computer assisted fields including Augmented Reality (AR), Virtual Reality (VR), computer graphics, medical imaging, visualization systems, and artistic fields. To support these systems, a variety of human controllable input devices and techniques have been developed to assist the modelling process. Clay and similar materials have been used for sculpting real models for many years.

One technique used to capture physical geometries is to measure the physical object and manually enter each dimension. Commercially available laser scanners allow the capture of complex geometries and generate digital presentations having a high polygon count. Such scanners are not designed for real-time manipulation tasks and deformations and corrections are usually needed to correct the captured model. Some systems use a number of photographs taken from different angles; which are processed manually to create a representation of the geometry of the photographed article. The Tinmith system uses pinch gloves and fiducial markers to track a user's thumbs allowing a range of computer aided design (CAD) like interaction techniques including construction at a distance, AR working planes, infinite carving planes, orthogonal laser carving, and creating a surface of revolution using AR. VR systems such as Virtual Clay provide an interactive freeform modelling environment. There also exists an interactive sculpting framework that encompasses modelling techniques based on the subdivision of solid geometries. It supports clay like manipulations, and more, allowing intuitive sculpting to be performed with physics based responses and haptic feedback using a phantom device.

Other input devices allow the creation, manipulation, and navigation of 3D geometries. The "two - 4 - six" input device is designed to support 3D manipulations with six degrees of freedom. It was designed for interactive presentations of virtual objects using multiple sensors as inputs. Orientation is tracked using gyroscopes and a rocker leaver, and an elastic touchpad is used to control rotation, translation, and manipulation operations. The Cubic Mouse is a cube-shaped input device with three rods that protrude through the faces of a cube. By pulling and pushing on the rods, motion is specified on the corresponding X, Y and Z axis. This input device also has 6 degrees of freedom (DOF) tracking to allow registration with a virtual environment.

Malleable surfaces are tracked using a camera mounted underneath a silicon membrane. The silicone membrane has coloured dots printed on its surface that are observed by the camera. Deformations can then be calculated in software allowing a reconstruction of the silicon's surface shape. A limitation of this form of malleable surface is that to construct a malleable spherical prop where all surfaces can be squashed is not simple since a support structure is required to hold the stretched silicon in place preventing depression in some locations.

BRIEF DESCRIPTION OF THE INVENTION

In an aspect of the invention a displacement sensor element includes an electrically conductive elastomeric member which is elastomeric along at least one axis and having at least one electrical characteristic that changes when the elastomeric member is compressed along the least one axis by a tactile force, and two conductive terminals located and in conductive contact with respective opposite sides of the elastomeric member in-line with the same at least one axis, such that between the two conductive terminals at least one electrical characteristic of the conductive elastomeric member is representative of the distance between the terminals.

In an embodiment of the invention the conductive elastomeric member is a foam material having gaseous voids.

In an embodiment of the invention at least one of the two conductive terminals is conductive fabric.

In accordance with the previous aspect of the electrical characteristic of the elastomeric member is one or more of the group consisting of voltage, current, resistance, dielectric constant, and capacitance.

In a further aspect of the invention a haptic sensor arrangement located on a supporting substrate for tactile actuation includes, at least two spaced electrically conductive elastomeric members, wherein each member is elastomeric along at least one axis and having at least one electrical characteristic that changes when the elastomeric member is compressed along at least one axis by a tactile force, each sensor located at a known position with respect to the supporting substrate; a tactile force transference member located over and between each sensor such that the tactile force transference member is arranged to change an electrical characteristic of at least one sensor in response to a tactile actuation; and a processor for measuring a said electrical characteristic of each sensor to determine a distance between the tactile force transference member and the supporting surface, and using the spacing between actuated spaced conductive elastomeric members to determine the position and displacement of the actuation with respect to the supporting substrate.

In an embodiment of the invention of a haptic sensor arrangement there is further non-conductive elastomeric material which has substantially the same elastomeric response characteristics as the conductive elastomeric member arranged to substantially fill the volume between spaced the conductive elastomeric members and electrically isolate the conductive elastomeric members from each other.

In accordance with the previous aspect of the invention the electrical characteristic of the elastomeric member is one or more of the group consisting of voltage, current, resistance, dielectric constant, and capacitance.

In an embodiment of the invention the electrical characteristic of the single axis displacement sensor is resistance.

An embodiment of the invention in accord with an embodiment of the haptic sensor arrangement, further includes an electrical terminal arranged to be in conductive contact with the tactile force transference member and the conductive elastomeric member, and an electrical terminal arranged to be in conductive contact with the conductive elastomeric member and abutment with the supporting substrate, both being terminals between which resistance is measured.

In an embodiment of the invention one or more characteristics of the haptic sensor arrangement are processed by the processor so as to substantially map a surface topology of the haptic force transference member with respect to the supporting substrate.

In an embodiment of the invention the haptic force transference member is electrically conductive fabric.

In yet a further aspect of the invention is a method of manipulating a computer menu used to operate and interact with a haptic input device to the computer, the steps of the method including, applying a tactile force to one or more locations on the haptic input device to select a menu input mode in the associated computer; orientating the haptic input device to change the menu selection; and applying a further tactile force or removing a previous tactile force to make the menu selection.

It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, or a computer readable medium such as a computer readable storage medium or a computer network wherein program instructions are sent over wireless, optical or electronic communication links. It should be noted that the order of the steps of disclosed processes may be altered within the scope of the invention.

Throughout this specification and the claims that follow unless the context requires otherwise, the words 'comprise' and 'include' and variations such as 'comprising' and 'including' will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

The reference to any prior art in this specification is not, and should not be taken as, an acknowledgment or any form of suggestion that such prior art forms part of the common general knowledge.

Specific embodiments of the invention will now be described in some further detail with reference to and as illustrated in the accompanying figures. These embodiments are illustrative, and not meant to be restrictive of the scope of the invention. Suggestions and descriptions of other embodiments may be included within the scope of the invention but they may not be illustrated in the accompanying figures or alternatively features of the invention may be shown in the figures but not described in the specification.

BREIF DESCRIPTION OF THE FIGURES

Fig. 1 depicts a pictorial representation of an embodiment of a displacement sensor;

Fig. 2 depicts a pictorial representation of an embodiment of an electrically conductive elastomeric member;

Fig. 3 depicts the sensor of Fig. 1 showing the result of an off-axis application of tactile force;

Fig. 4 depicts a pictorial representation of an embodiment of a dual sensor arrangement;

Fig. 4a depicts a pictorial representation of a computer device used in association with a sensor arrangement;

Fig. 5 depicts a picture of an embodiment showing a PCB array of conductive terminals;

Fig. 6 depicts a picture of the embodiment associated with Fig. 5 showing electrically conductive elastomeric members;

Fig. 7 depicts a picture of the embodiment associated with Fig. 5 showing non-conductive elastomeric material;

Fig. 8 depicts a picture of the embodiment associated with Fig. 5 showing the covering of the partially assembled sensor array with tactile force transference member being conductive fabric;

Fig. 9 depicts a picture of the embodiment associated with Fig. 5 showing the use of a sensor array by a user;

Fig. 10 depicts a digitally created representation of the tactile depression of the embodiment associated with Fig. 5;

Fig. 11 depicts a perspective view of the layout 162 evenly spaced sensors on a sphere's surface generated using a subdivision algorithm;

Fig. 12 depicts a perspective view of a custom mould used for casting foam;

Fig. 13 depicts a perspective view of a custom cast foam insulation;

Fig. 14 depicts a perspective view of an array of conductive foam inserts inserted into a foam mould;

Fig. 15 depicts a perspective view of the digital foam sphere showing external electrical terminals, and on/off switch, antenna, and charging port;

Fig. 16 depicts a perspective view of a fully constructed spherical digital foam input device;

Fig. 17 depicts a perspective view of a digital representation of a three-dimensional form showing ray intersection and surrounding vertices calculation representation;

Fig. 18 depicts a perspective view of a digital representation of a three-dimensional form showing the resulting geometry after a single clutched free-form sculpting operation, as shown in Fig. 19;

Fig. 19 depicts a perspective view of a clutching tilt operation to reset the vertex locations;

Fig. 20 depicts an illustration of the half hemisphere technique where the user performs sculpting with farm, and unwonted finger presses at the back of the sphere in the back hemisphere;

Fig. 21 depicts an illustration of the half hemisphere correction being performed, with active vertices shown on the right side, in active vertices shown on the left side;

Fig. 22a depicts an illustration of a user controlling the camera location with press location, and zoom with pressure;

Fig. 22b depicts an illustration of the camera location transition instigated by the user control illustrated in Fig. 22a;

Fig. 23 depicts a menu operating procedure with the user interaction pose illustrated adjacent the interaction mode digital representation;

Fig. 24 depicts a menu operating procedure with user interaction including a rotation of the prop upside down along with the appropriate menu selection highlighted; and

Fig. 25 depicts a menu operating procedure with user interaction including the use of a rotating the prop around a heading so as to select different menu options with the appropriate menu selection scrolling in concert with the actions.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Both a displacement sensor element and a haptic sensor arrangement using two or more displacement sensor elements are described herein. The arrangements can be used for real-time capture of the shape of haptic deformation of the sensor arrangement. Although the embodiments described in detail herein are primarily directed to tactile applications the sensor can be used in the machine, robotic and medical fields where a sensor of this type can usefully be applied where only machine or computer controlled robotic elements are interacting, particularly if the machines or robotic elements are being used in human like applications but other force measurement applications are possible.

In an embodiment the sensor element and an array of such sensor arrangements, use the variable resistive properties of conductive foam an example of which is obtainable from RS Components Pty Ltd of 25 Pavesi Street, Smithfield, NSW, Australia having catalogue number 550-066 and in the same embodiment covered by a conductive fabric, an example of which is obtainable from Less EMF of 809 Madison Avenue, Albany, NY, USA having catalogue number A251.

By measuring the voltage difference across the conductive foam when it is compressed, a repeatable and accurate measurement of the distance between the surface of the sensor and the supporting substrate is obtained. The substrate can be of a variety of shapes and in one embodiment disclosed the form is of a plane and in another embodiment in the form of a spheroid, over which the sensor arrangement is constructed so that the tactile force responsive surface provided by the haptic sensor arrangement can be mapped directly to the supporting substrate of the embodiment. From those measurements the physical topology of the embodiment is used to create a matching geometry in the form of a digital representation, which in turn can be displayed in real-time or stored for later use.

In one example of the use of the embodiments, as the user of the embodiment applies tactile force to the surface of the haptic sensor arrangement the elastomeric property of the arrangement provides a tactile response which is useful in providing a realism to the interaction of the user with the arrangement. Since the sensor arrangement eventually returns to an unbiased elastomeric state thus restoring the surface to a known state, the user can re-use the same or a varying tactile force to further adjust the shape of the digital representation provided in real-time. Different foam materials exhibit different restoration characteristics and in one example, the foam returns to 90% of its original size “almost immediately” and the remaining 10% will take a maximum of 24 hours to return. Another way in which the sensor can be used is to allow for a successive application of tactile force to be cumulative to a prior application of tactile force so that the user sees a cumulative effect on the digital representation, which would be much like a real tactile interaction with a malleable object.

The digital representation can also be used for creating other digital mappings and representations usable in a variety of ways, some examples of which include, VR, AR and 3D and 2D modelling, computer graphics, medical imaging, visualisation aids and the arts.

Two embodiments of haptic sensor arrangements are disclosed and shown in use as input devices that allow real-time capture of their physical manipulation using tactile forces.

Fig. 1 depicts the operation of a single foam sensor. As the foam is depressed, the resistance of the foam reduces, which is but one of the many electrical characteristics of the foam which can be measured. Indeed, the use of foam is but an example of an electrically conductive elastomeric member and the measurement of resistance is but one of the many electrical characteristics the member has, which can include voltage, current, dielectric constant and capacitance. These characteristics can be measured across the member with and sometimes without the use of electrical terminals located on opposite sides of the member.

The electrically conductive elastomeric member has at least one axis (shown by the vertical dotted line) along which the member can be compressed/deformed and the arrangement of electrical terminals in electrically conductive contact with the member on opposite sides but located in-line with at least one of those axes allows for measurement to be performed between those terminals.

In this embodiment the initial resistance of a 24mm thick piece of foam is 20k Ohms and when depressed to 2mm the resistance changes to 1.5k Ohms. Figure two depicts pictorially the range of deformation of the foam, wherein the open cellular array of foam material is depicted clearly at the right hand side of Fig. 1 and as the depression distance increases the foam thickness decreases as the gas within the cellular array is expelled and the walls of the cells deform. In this embodiment the gas expelled is the atmospheric gasses referred to as air. Other foam embodiments may use a closed system and the gasses may be specifically chosen for the application to hand.

One way of converting the measurement is to use a voltage dividing circuit and an analogue-to-digital converter (ADC) to calculate the then current size of the foam sensor. The ADC is connected to an MSP430 microcontroller allowing those real-time readings from the foam sensors to be processed and sent in digital form to a computer device which includes memory, a Central Processing Unit and programmes to run the computer to store and further process the digital form of the measurements taken.

Fig. 3 depicts the deformation of the sensor which is not along the axis but it will be noted that there is still a deformation of a portion of the conductive elastomeric material as illustrated by the distance X1 being larger than the distance X2 and more importantly there is a change in at least one of the electrical characteristics of the conductive elastomeric material, such as in this embodiment the resistance.

Fig. 4 depicts a haptic sensor arrangement 40 located on a supporting substrate 42 for tactile actuation from above the sensor arrangement. The arrangement includes, at least two spaced electrically conductive elastomeric members 44, and 46 in this embodiment conductive foam, wherein each member is elastomeric along at least one axis (as depicted by the vertical dotted lines). The electrically conductive elastomeric members have at least one electrical characteristic that changes when the elastomeric member is compressed along the least one axis by a force, such as a tactile force which has been used as an example and described earlier in this specification. Each sensor is located at a known position with respect to the supporting substrate. A tactile force transference member 48 is located over and between each sensor such that the tactile force transference member is arranged to change an electrical characteristic of at least one sensor in response to a tactile actuation, such as being depressed by a finger 50 of a user of the sensor arrangement.

The tactile force transference member 48 in this embodiment is a stretchy conductive fabric and the feel of the combination of the fabric and the elastomeric members assists in the feel of the sensor arrangement and in particular the feel of the elastomeric members.

Also depicted in Fig. 4 is one portion of a non-conductive elastomeric material 52 which has substantially the same elastomeric response characteristics as the conductive elastomeric members 44 and 46 arranged to substantially fill the volume between spaced conductive elastomeric members and electrically isolate the conductive elastomeric members from each other.

The isolation provided by this non-conductive member is not absolutely required as interference, noise and shorting of elements can be modelled out or used to reduce the level of such otherwise negative affects.

Two separated electrical terminals 54 and 56 are arranged to be in conductive contact with the conductive elastomeric member and abutment with the supporting substrate, both being terminals between which resistance is measured when used in conjunction with and in electrical contact with, either a single conductive tactile force transference member 48 (as depicted in Fig. 4 and which can be a conductive fabric) or individual electrical terminals (as will be depicted in other figures associated with another embodiment) and the conductive elastomeric members 44 and 46. Measurement of the chosen electrical characteristic can be made between the terminals 56 and 54 and the conductive fabric 48.

Fig. 4a depicts and ADC 60, a micro-controller 61 and a processor 62 with associated memory 64 and visual display 66 for transforming the electrical measurements of the electrical characteristic of each sensor and for determining a distance between the tactile force transference member 58 and the supporting surface 42 (or any other relative surface or reference point or area, as the adjustment can be readily performed by one skilled in the art), and using the known spacing between each actuated spaced conductive elastomeric members to determine the position and displacement of the actuation with respect to the supporting substrate.

For ease of use the term “Digital Foam” will be used to refer to this embodiment but it not in any way meant to be limiting on the material used for the conductive elastomeric member.

The embodiment shown in Figs 5, 6, 7, 8 and 9 uses one hundred (10 x 10) foam sensors as depicted in Fig. 6 producing a 90mm x 90mm working area and a working depth of 20mm. This was chosen so that the construction was not too complex while at the same time providing sufficient resolution to allow multiple fingers to press the foam surface without overlapping. One hundred terminals were etched onto a printed circuit board (PCB) as shown in Figure 5. If a single un-insulated conductive foam piece was used over the hundred terminals, co-incident in time multiple depressions of the foam provide a shorter path of resistance and an incorrect reading can be measured. To overcome this limitation, a custom piece of foam that combines ordinary non-conductive polyurethane with conductive polyurethane Figs. 6 and 7 provides an insulation layer for each discrete sensor so as to remove or reduce the interference possibility associated with closely located sensors.

A sheet of conductive fabric was laid over the top of the sensor array to complete the circuit.

The final input device is show in Fig. 9 where a user is shown depressing two separate locations with their index fingers. The corresponding geometry shown in Fig. 10 is a digital representation of the surface of the conductive fabric covering but is inverted to avoid occlusions in the figure and to verify two finger presses are visible.

Even having a working area large enough to have two users operate the input device with both hands it was still possible to avoid overlapping on the resulting digital representations of the tactile geometry of the conductive fabric covering. Since the flat form of the Digital Foam senses each point associated with a terminal separately, the processing output shows no shadowing effects as can occur with standard touch screens.

It is possible to array multiple copies of a Digital Foam sensor array side by side. This combination of multiple flat Digital Foam arrays can be scaled up to areas large enough to cover table top surfaces with such sensors.

Each of the foam sensors is attached to a 10-bit ADC. The length of the foam sensor determines the resolution achieved. Given a 20mm thick piece of foam, a 10-bit ADC provides 1024 levels that change depending on how far the foam is depressed. The initial 20mm thick foam size was chosen for ease of construction although we are currently experimenting with more precise electronics to help maintain the maximum resolution while increasing the operating length.

Sensor readings are transmitted at 30Hz with a latency of less than 8ms with one hundred sensors. As the number of foam sensors increases additional ADC's channels are required increasing the read time. As the number of foam sensors is increased additional ADC's are required increasing the sequential read time.

3D geometry creation often starts with a base shape on which carving and other operations are performed to generate a sculpted solid.

Constructing a multi-sensor arrangement in a spherical shape as is the form of the embodiment described herein has difficult technical problems to overcome.

First, constructing a foam surface in a sphere shape with a large number of sensors requires custom construction techniques to be developed. The position of the sensors is preferably placed equidistant about the sphere's surface. A subdivision algorithm and a repelling algorithm were used. The subdivision algorithm generates perfectly evenly spaced vertex locations but only certain numbers of vertices are possible. The algorithm starts with one of the five platonic solids and is reduced by dividing each face into four new faces until the desired complexity is reached. By choosing different base platonic solids and performing different division levels there are a large number of evenly spaced vertex spacing’s can be generated. Alternatively a repelling algorithm can generate “almost evenly spaced points” with N vertices. The subdivision technique was used to determine the location of the 162 sensor embodiment disclosed. An icosahedron (20 faces, 12 vertices and 30 edges) was chosen as the base shape and performed 2 levels of subdivision so the final shape has 320 faces, 162 vertices and 480 edges. The sensor layout is shown in Fig. 11.

Secondly, the digital converters (ADC's) in a confined location technically required very careful design and construction to accommodate the dense electronics. The electronics used in the 162 sensor Spherical Digital Foam embodiment ADCs were used to measure the resistance of each conductive foam sensor. In total there are 16 TLV1543s each with 11 channels that allow the capture of a 10 bit sample for each of the 162 foam sensors (Exposed sensor terminals shown in Fig. 15. Separate boards were created for each ADC chip and attached to the inner surface of the plastic skeleton; this was done to optimize space usage within the sphere. Each ADC chip is connected to a common serial data bus that is managed with a Texas Instruments MSP430F1232 microcontroller. Wireless communications to the microcontroller are performed using a Parani-ESD210 Bluetooth module which has an external antenna. All communications to the Digital Foam are performed over a

Bluetooth connection when a corresponding device is embedded or associated with each Digital Foam input array. Each Digital Foam input array has its configuration stored on the associated hardware. When a connection is made, the configuration describing the device's shape, sensor locations, and a tessellation order is provided.

An external antenna protrudes though the conductive fabric outer Fig. 16. Signal loss is not a problem using the external antenna but an internal antenna is not excluded from future designs. Since the conductive fabric is connected to a ground signal and as such acts similar to a Faraday cage blocking wireless signals. To allow a wireless connection it is possible to provide spaced holes in the conductive fabric for allowing a 2.4 GHz Bluetooth signal to be transmitted for both the foam and orientation sensors. The external antenna location of the described embodiment also doubles as a reference orientation marker as will be discussed.

The sphere contains a MSP430F1232 a microcontroller, ADC, Intersense Inertia Cube 3 available from {http://www.intersense.com/}, a 600mAh Lithium Polymer battery, and Bluetooth wireless electronics. An ON/OFF switch, exposed connection terminal and a battery charging terminal is shown external of the isolated sensor covered sphere in Fig. 15 which can be accessed when required as they would reside within the sphere during use.

The foam sensors attached to the supporting sphere are depicted in Fig. 14, the insulation cover of fig. 13 fitted about the foam sensors is depicted in Fig. 13, and the final shape showing the conductive fabric outer is shown in Fig. 16.

Insulating the individual foam sensors and maintaining good contact at the termination points is critical to the performance of each sensor. One method of positioning sensors is for each sensor to be separately attached a plastic sphere. This approach is tedious and not scalable as the number of sensors is increased. The embodiment described uses liquid foam poured into a custom mould (as shown in Fig. 12. Smooth On's FlexFoam-iT! {available from http://www.smooth-on.com/} liquid foam was poured into the custom mould to create the insulating and structural part of the foam sensor as shown in Fig. 13. Once the moulding process is completed, individual conducting foam inserts are placed into each of the holes Fig. 14. The insulating part of sphere's foam surface is created in two halves to ease the complexity of construction and allow assembly and disassembly of the device.

To reveal Digital Foam's potential an interaction technique to support 3D modelling has been developed. For the purposes of the development the assumption was used that Digital Foam would be used as a sole input device. The outcome is a technique for modelling and interactions that can be performed without the need for a keyboard or mouse, a common requirement when using virtual and augmented reality systems. This also removes the need for the user to put the input device down to free their manipulating hands to use a keyboard or mouse instead of the in hand input device. Although speech input is a possible command entry technology, a single device for command entry and direct manipulation of the object's surface was deemed necessary.

The Spherical Digital Foam input device can be used with interaction techniques that support 3D modelling operations. Firstly we have an option to load existing 3D models into the application. A user can now begin the modelling process with either the reconstructed shape generated by the hardware device or by loading an existing 3D model. To allow manipulations to be performed on existing models the Digital Foam sensors are mapped to locations associated with the model allowing semi-direct manipulation to be performed. The mapping is described as semi-direct because the input device shape is not the same as the 3D model. However a spatial mapping is maintained between the two.

To achieve the mapping between the 3D model and Digital Foam form, a set of rays aligned with each of the conductive foam sensors are cast from the centre of the 3D model to find the intersection points on the outer surface of the 3D model Fig. 17. Once each intersection point is found, an index to each vertex is stored for later use. The length of each Digital Foam sensor is mapped directly to these intersection points, as described in Equation 1 below, allowing the user to modify the 3D model by pressing on the Digital Foam surface. The new vertex location P' is found by translating the original position P in the direction of the ray using the foam length as the scalar value.

Equation 1 $P' = P * (su * fl)$

Where,

P = Intersection point on model's outer surface.

fl = Current length of the foam sensor.

su = Normalized Digital Foam vertex location.

To increase the working area between sensor points an algorithm is applied to find the closest surrounding vertices within a user defined radius. After calculating the surrounding vertices for each intersection point and storing them in ascending order based on length from the intersection point (P) to each vertex (V) on the model. For each vertex (V) within the user defined radius we find V' (the set of new vertex locations) by scaling the foam length (fl) by length between the intersection point (P) and the vertex V, see Equation 2, below. The furthest vertex within the predefined radius has no modification, generating a curved indentation shape used to perform sculpting Fig. 18.

Equation 2

$V' = V * ((su * (fl * |fd - vd|^2 * c)$

where,

V = Current vertex.

su = Direction pointing out from the centre of the model.

fd = Length from the furthest vertex to P.

vd = Length from the current vertex to P.

c = Scale factor.

The Spherical Digital Foam employs a tilt based clutching mechanism to allow accumulative modelling operations. A user performs a sculpting operation by pressing the foam to the desired location, tilts the prop approximately 20 degrees, and releases their finger. Each of the vertex positions is stored and the process can be repeated using the clutching operation shown in Fig. 19.

Manipulation direction (push in or push out the 3D virtual model) can be set allowing the inverse operation to be performed, since artists commonly attach and detach clay to a physical model during its creation. The user can change the direction by toggling a menu option. The combined techniques discussed here allow the modification of vertices to be either additive or subtractive. Fig. 18 shows a resulting sculpting operation depressing the left cheek of the digital representation.

One method of manipulating a computer menu used to operate and interact with the haptic input device includes the steps of applying a tactile force to one or more locations on the haptic input device to select a menu input mode in the associated computer, orientating the haptic input device to change the menu selection; and applying a further tactile force or removing a previous tactile force to make the menu selection. The Figures 23, 24 and 25 illustrate embodiments of the basic functionality of such steps, which are described in greater detail later in the specification.

Some general observations can be made about the design aspects of Digital Foam. Unlike Surface drawing the user can begin their task with a fixed volume and perform sculpting operations immediately. This approach emulates clay sculpting using a single solid piece of modelling clay.

A Digital Foam input device can be used with Surface Drawing techniques and it is envisaged that a new sense of control could be added so as to allow larger surface areas to be modified perhaps in a collaborative manner. Furthermore, the user does not need to see the prop while manipulating it and there are no erroneous effects with the haptic feedback. Yet further, Digital Foam can capture the fingertip location

When holding a Spherical Digital Foam input device, a user's fingers and thumb may cause depressions in more than one location on the foam surface. This is problematic when free-form modelling, as these could be interpreted as unwanted modelling gestures. For example, when a user performs sculpting operations at the front of the sphere using their thumbs, their fingers are located at the back of the sphere causing depressions at both the front and the back as shown in Fig. 20.

The technique developed divides the sphere's operation surface into two hemispheres, front and back. All vertices located on the front hemisphere relative to the user's view point remain active, while those behind are made inactive Fig. 21. On initialization, the user specifies the front orientation and can not move their head position or orientation during operation (Additional trackers are required on the users head and Digital Foam to achieve this). As the user rotates the Spherical Digital Foam input device the virtual model's orientation is updated in real-time using an internal orientation sensor. To maintain the half hemisphere operation, all vertices that are in front of the centre point are flagged as active while those behind are inactive. This operation overcomes a significant user interface problem when operating Digital Foam; thus allowing easier operation and increased control during modelling. The half hemisphere operation can be applied to work in conjunction with other techniques allowing stacked operations to be performed. For example, half hemisphere operation can be used with sculpting or menu click operations.

A camera view control technique has been developed allowing a user to quickly and intuitively move the virtual cameras position. Figs. 22a and 22b depicts the operation of the Digital Foam sphere in the camera view control mode. While in the camera view control mode, a user touches any part of the surface of the sphere and the camera viewpoint will be shifted to the matching location. When multiple sensor readings (depressions) are detected, the foam sensor with the shortest value is used to determine the camera position. The direction of the camera is determined in a similar fashion to an orbital view algorithm. A bounding sphere is created around the virtual model and the direction of the camera is set to look at the centre of the object. The user can also control the zoom of the camera based on the pressure of the touch. As the user pushes on the Digital Foam harder the camera zooms in closer and as the user releases the zoom location returns.

A custom menu system has been developed as the primary command entry technique used when operating the Spherical Digital Foam input device. The navigation of the menus is designed to be intuitive, quick and easy to use so as minimal user training is required. There are a number of challenges that need to be addressed to use Digital Foam as a sole input device for both command entry and direct manipulation. Such as free-form sculpting, camera view and all modes of direct model interaction are referred to as *interaction modes*. A technique is implemented that allows the user to transition from any interaction mode into a *menu mode* without using additional input devices.

To transition from *interaction mode* to *menu mode* the user rotates the input device up-side-down so the roll or pitch is beyond a predefined threshold value (currently set to 90 degrees and shown in Fig. 23. Once in the menu mode, the user can navigate through menus by rotating the input device around the heading (vertical) axis. There are 10 configured menu options allowing the user to select different interaction modes, but as the number increases, there can be additional hierarchical menus. To scroll through menu options a transition of 20 degree intervals has been chosen. When the user rotates around the heading axis the selected menu option changes from one menu option to the next every 20 degrees Fig. 25. Currently ten menu items are displayed on two rows with five menu items on each row. A transition from row one to row two occurs when the last item in row one is reached. By rotating the input device beyond the last item in row two a transition to the first row occurs.

Once the correct option is selected, a menu selection operation is required. To achieve this the Digital Foam sensors are actuated, by squeezing the input device with one or two hands a menu selection operation is performed. In software this is determined when the average value over all sensors drops below a predefined threshold and a click event is generated. Finally once the option has been selected and clicked, the menu is hidden and the selected interaction mode becomes immediately active.

To re-enter the menu mode, the input device orientation must first return so as rotation values are above the predefined threshold. Once this has occurred the device can be turned up-side-down again to enter menu mode. Figs. 23, 24 and 25 shows the different states of the menu selection operation.

One limitation of this technique is that when operating in modes that map the orientation sensor directly to the model, the menu mode may be accidentally entered. Although this is a limitation, rotating around the heading is most commonly used for model navigation and both pitch and roll are unaffected until they pass the threshold value (currently set at 90 degrees).

This following disclosure presents a collection of common interaction techniques, such as rotation and scale. The Spherical Digital Foam has the unique feature of pressure sensing of the user's interaction, and an explanation of how to exploit this feature is presented.

There are two model rotation control modes disclosed. The first uses a direct mapping between the values of internal orientation sensor and the 3D model. The updating model rotation can be used in conjunction with other techniques such as free-form sculpting to adjust the current view angle. A menu option can be toggled to turn rotation on and off, however this mode is stateless and the model can not be set to a user defined position once this interaction mode is left.

To overcome this problem a second rotation control mode is available that allows a default rotation angle to be set. When using “set rotation” no rotation transformations are performed until the user begins squeezing the Digital Foam input device. When the desired operating angle is selected the user stops squeezing the input device and this angle is recorded and used as a default model orientation for all other interaction modes.

Scale functions of the model are used and there are eight separate scale operations. Each is activated by squeezing the Digital Foams surface to directly alter the scale value. The scale can be altered on X, Y or Z axis separately or a combined operation where the overall model's size is altered. The direction of scale can also be toggled via the menu.

Digital Foams' unique pressure sensing surface can gather pressure data that may be processed with different methods depending on the task being performed. Capturing the speed of a press for each separate sensor on the Digital Foam surface is possible. This is done by keeping a buffer for each foam sensor that records its distance and a time value. For example, keeping a ring buffer with a size of 20 is adequate to capture a range of button press/release speeds.

One limitation of the physical properties of the conductive foam is intense compression of the foam sensors has a slow return when depressed beyond approximately 80% of its original size. Avoiding the pressing of the sensors too hard or the use of a mechanical stop may reduce or avoid the described limitation.

When using the menu system, free-form sculpting or the camera view technique, it is useful to have a marker on the physical device to identify the top of the sphere. The physical marker can be the external antenna exiting point on the Spherical Digital Foam input device or if one does not exist then a physical marker can be placed on the sphere. A matching software marker can also be toggled on and off via the menu. This simple technique provides a spatial reference between the physical sphere and the representational 3D model.

The creation of an adequate resolution Spherical Digital Foam has inspired a technique that identifies unique areas of the foam's surface that can be configured in run-time to set up active regions for different operations. For example, the system prompts the user to configure a ``left click", in turn the user would depress the desirable area of the spherical prop for their personalized ``left click" operation. The application would then record the surface selected and the tactile force applied so that to interpret a ``left click" operation appropriate force in a specific region will trigger the desired action using Hidden Markov Models to assist the transition from tactile force so the appropriate action can be applied.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A displacement sensor element includes an electrically conductive elastomeric member which is elastomeric along at least one axis and having at least one electrical characteristic that changes when the elastomeric member is compressed along the at least one axis by a tactile force, and two conductive terminals located and in conductive contact with respective opposite sides of the elastomeric member in-line with the same at least one axis, such that between the two conductive terminals at least one electrical characteristic of the conductive elastomeric member is representative of the distance between the terminals.

2. A displacement sensor according to claim 1 wherein the conductive elastomeric member is a foam material having gaseous voids.

3. A displacement sensor according to claim 1 wherein at least one of the two conductive terminals is conductive fabric.

4. A displacement sensor according to claim 3 wherein the electrical characteristic of the elastomeric member is one or more of the group consisting of voltage, current, resistance, dielectric constant, and capacitance.

5. A haptic sensor arrangement located on a supporting substrate for tactile actuation includes,

at least two spaced electrically conductive elastomeric members, wherein each member is elastomeric along at least one axis and having at least one electrical characteristic that changes when the elastomeric member is compressed along the least one axis by a tactile force, each sensor located at a known position with respect to the supporting substrate;

a tactile force transference member located over and between each sensor such that the tactile force transference member is arranged to change an electrical characteristic of at least one sensor in response to a tactile actuation; and

a processor for measuring a said electrical characteristic of each sensor to determine a distance between the tactile force transference member and the supporting surface, and using the spacing between actuated spaced conductive elastomeric members to determine the position and displacement of the actuation with respect to the supporting substrate.

6. A haptic sensor arrangement according to claim 5 further including a non-conductive elastomeric material which has substantially the same elastomeric response characteristics as the conductive elastomeric member arranged to substantially fill the volume between spaced conductive elastomeric members and electrically isolate the conductive elastomeric members from each other.

7. A haptic sensor arrangement according to claim 5 wherein the electrical characteristic of the elastomeric member is one or more of the group consisting of voltage, current, resistance, dielectric constant, and capacitance.

8. A haptic sensor arrangement according to claim 5 wherein the electrical characteristic of the single axis displacement sensor is resistance.

9. A haptic sensor arrangement according to claim 5, further includes an electrical terminal arranged to be in conductive contact with the tactile force transference member and the conductive elastomeric member, and an electrical terminal arranged to be in conductive contact with the conductive elastomeric member and abutment with the supporting substrate, both being terminals between which resistance is measured.

10. A haptic sensor arrangement according to claim 5, wherein one or more characteristics of the haptic sensor arrangement are processed by the processor so as to substantially map a surface topology of the haptic force transference member with respect to the supporting substrate.

11. A haptic sensor arrangement according to claim5, wherein the haptic force transference member is an electrically conductive fabric.

12. A method of manipulating a computer menu used to operate and interact with a haptic input device to the computer, the steps including;

a. applying a tactile force to one or more locations on the haptic input device to select a menu input mode in the associated computer;

b. orientating the haptic input device to change the menu selection;

c. applying a further tactile force or removing a previous tactile force to make the menu selection.

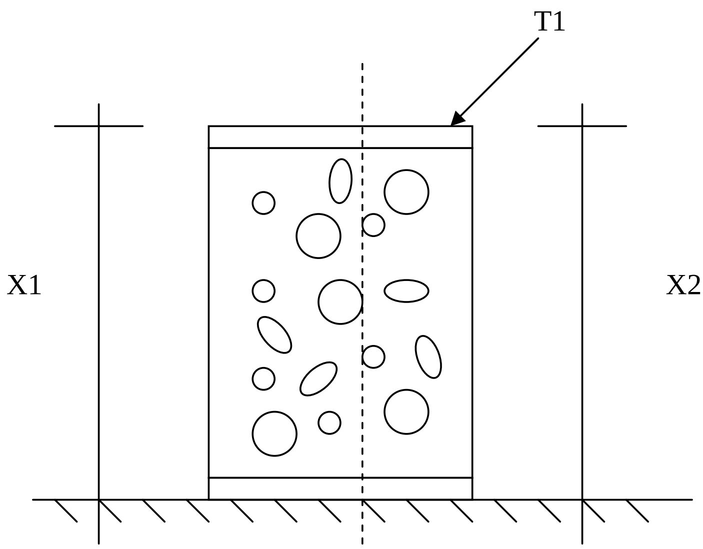


FIG. 1

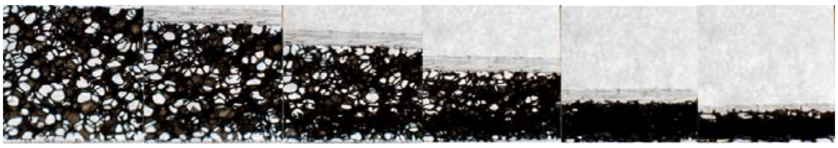


FIG. 2

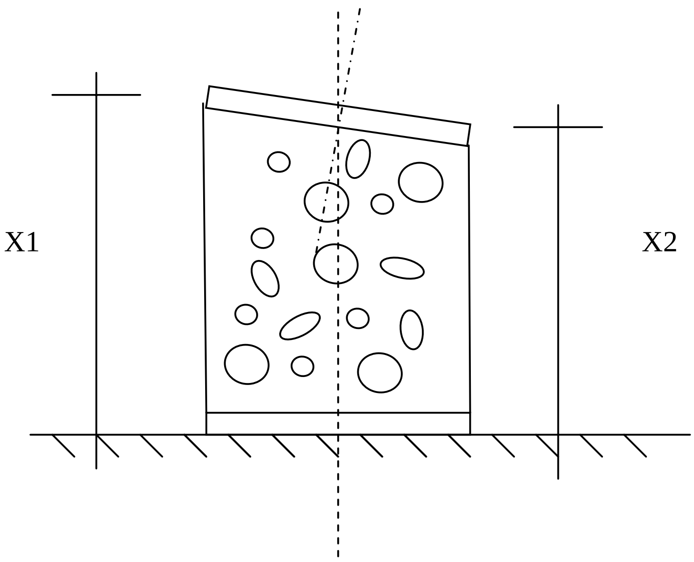


FIG. 3

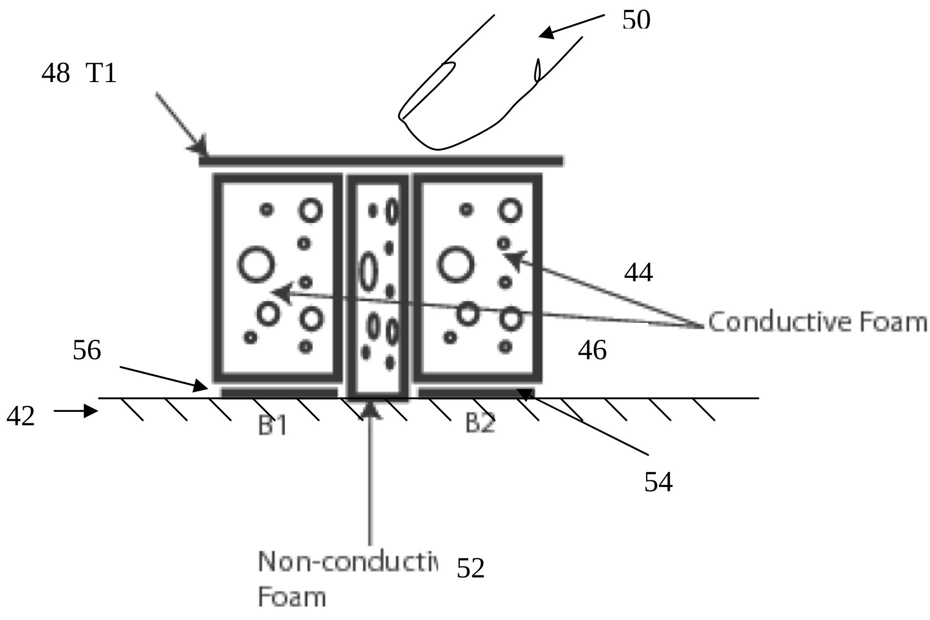


Fig. 4

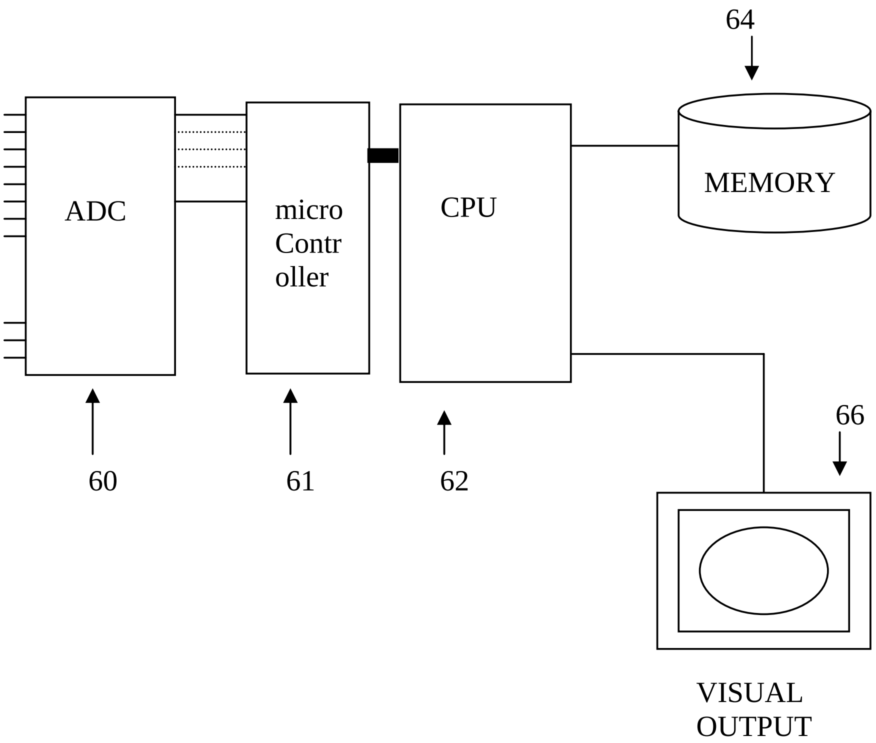


Fig. 4A

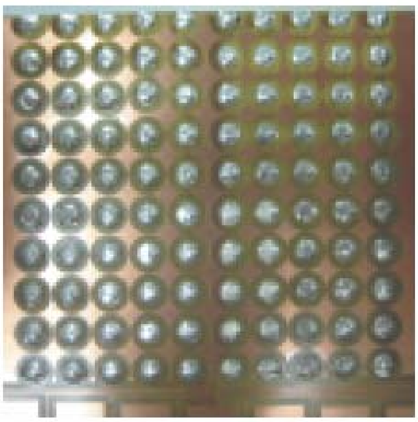


Fig. 5

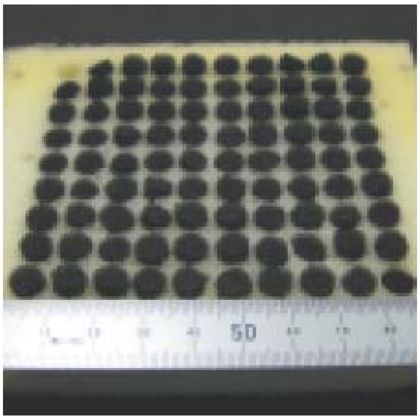


Fig. 6

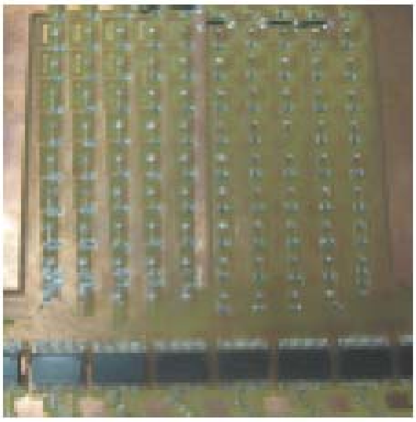


Fig. 7

Fig. 8

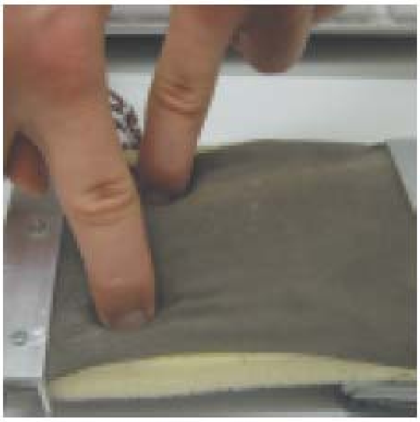


Fig. 9

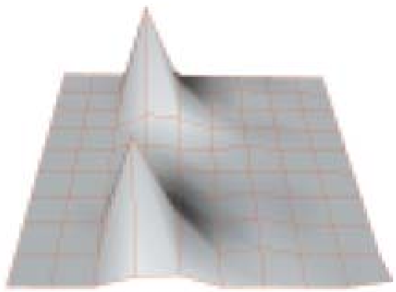


Fig. 10

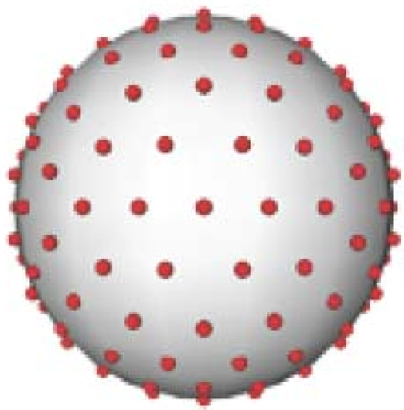


Fig. 11

Fig. 12

Fig. 13

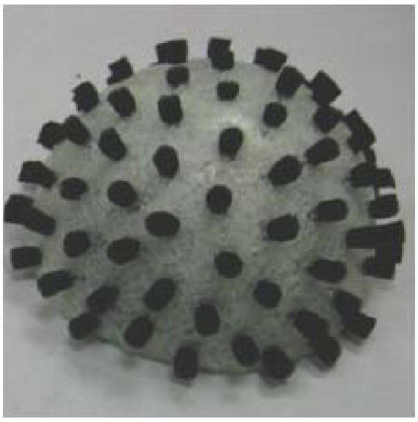


Fig. 14

Fig. 15

Fig. 16

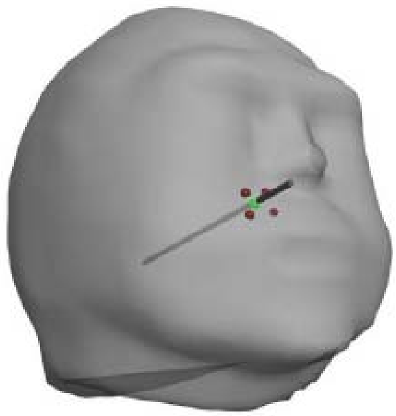


Fig. 17

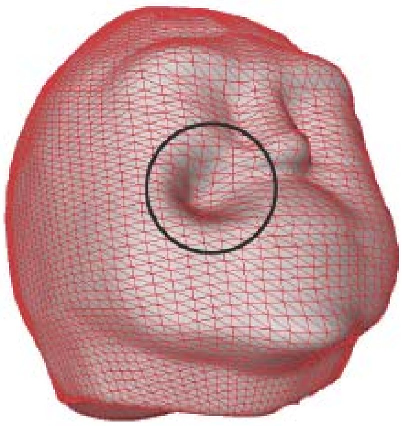


Fig. 18

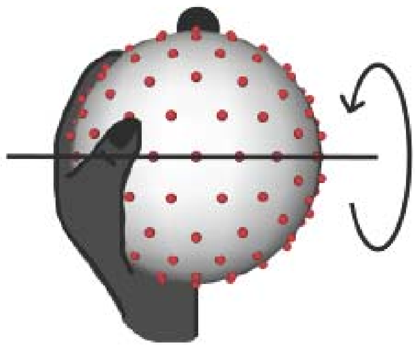


Fig. 19

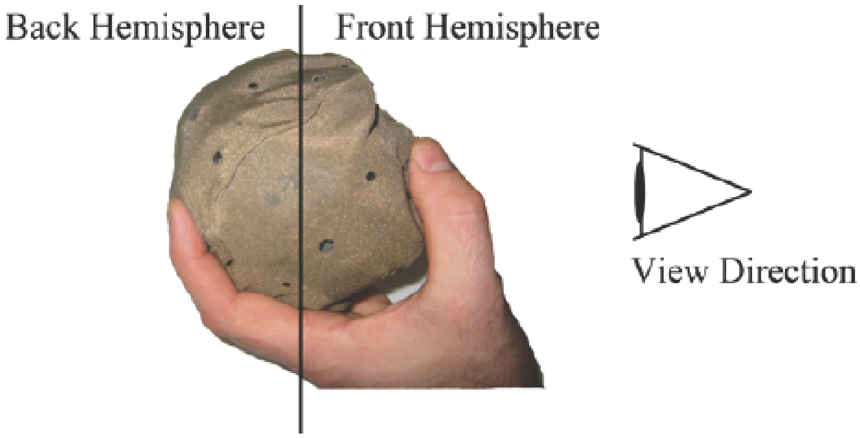


Fig. 20

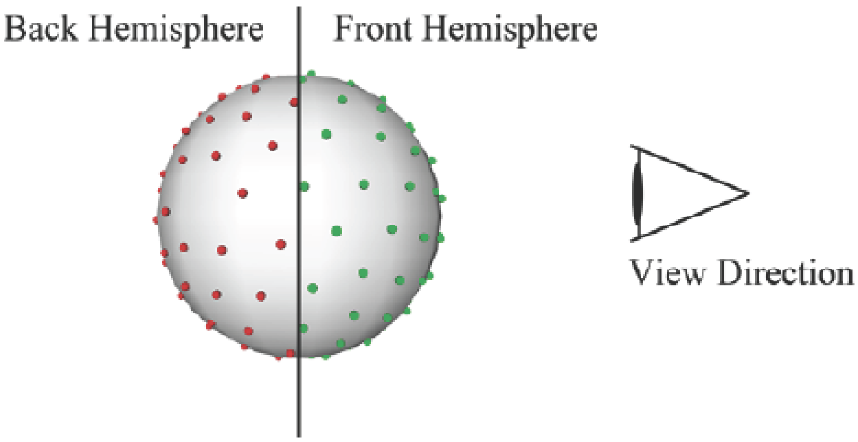


Fig. 21

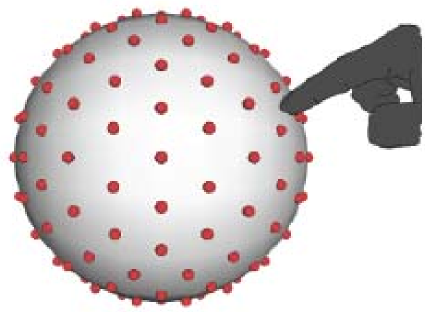


Fig. 22A

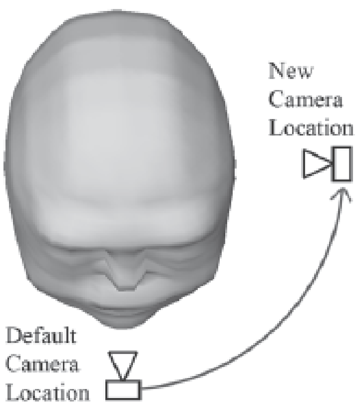


Fig. 22B

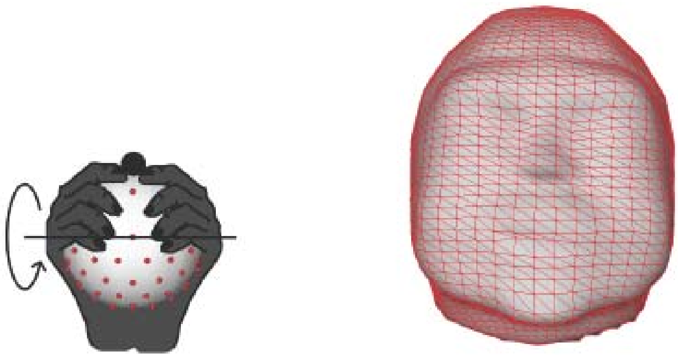


Fig. 23

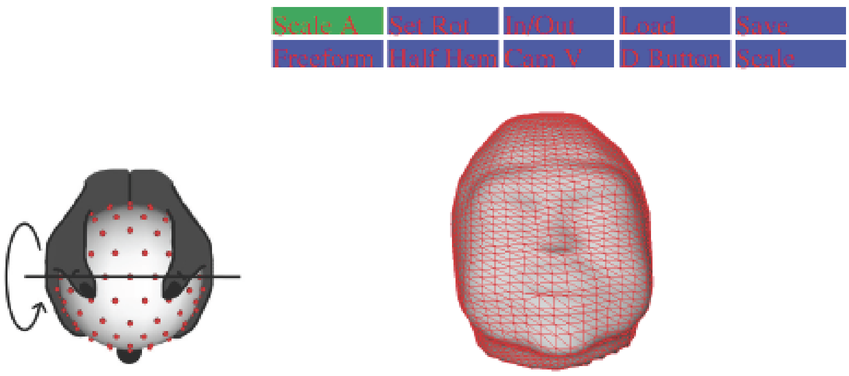


Fig. 24

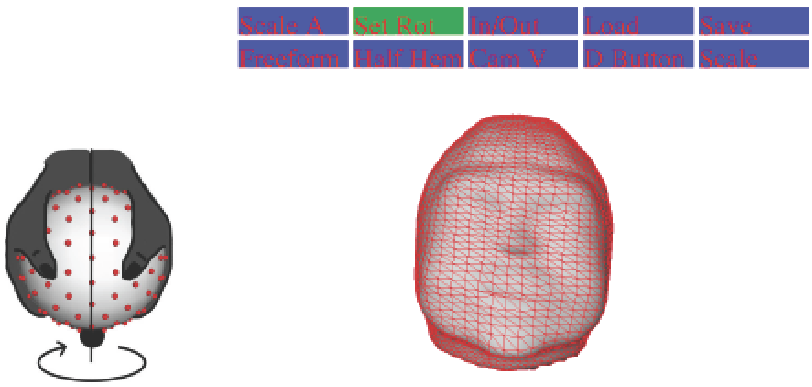
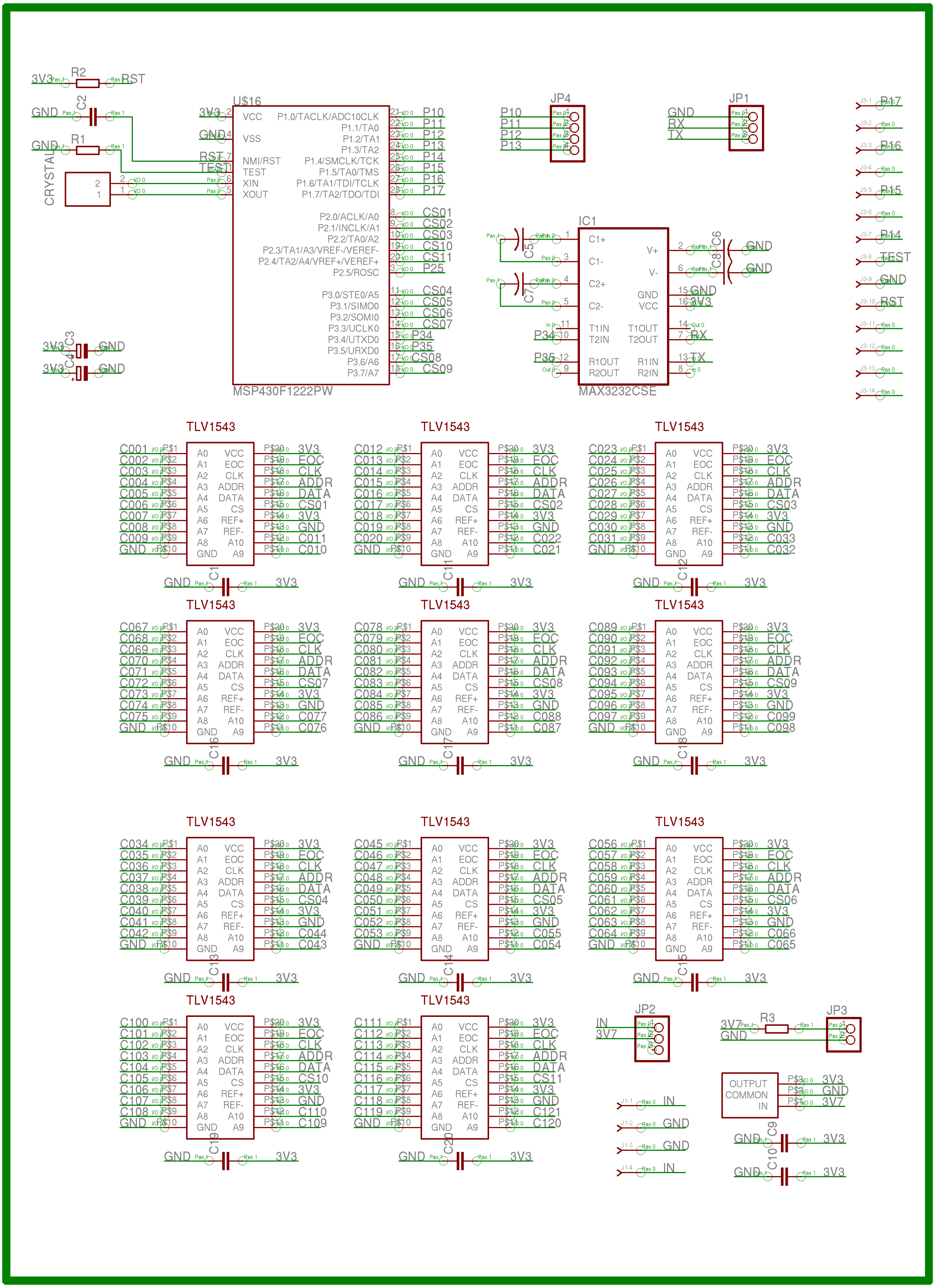


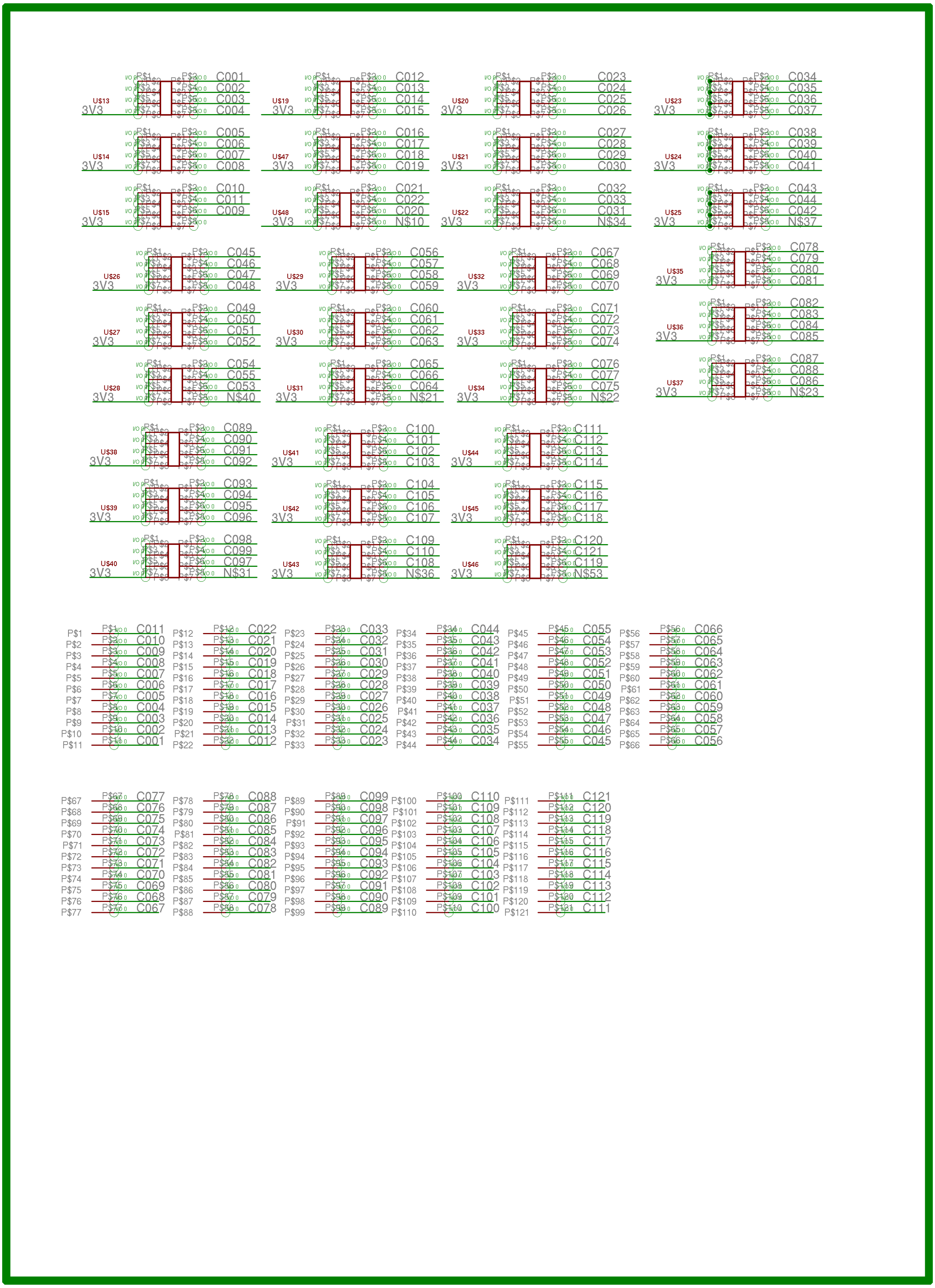
Fig. 25

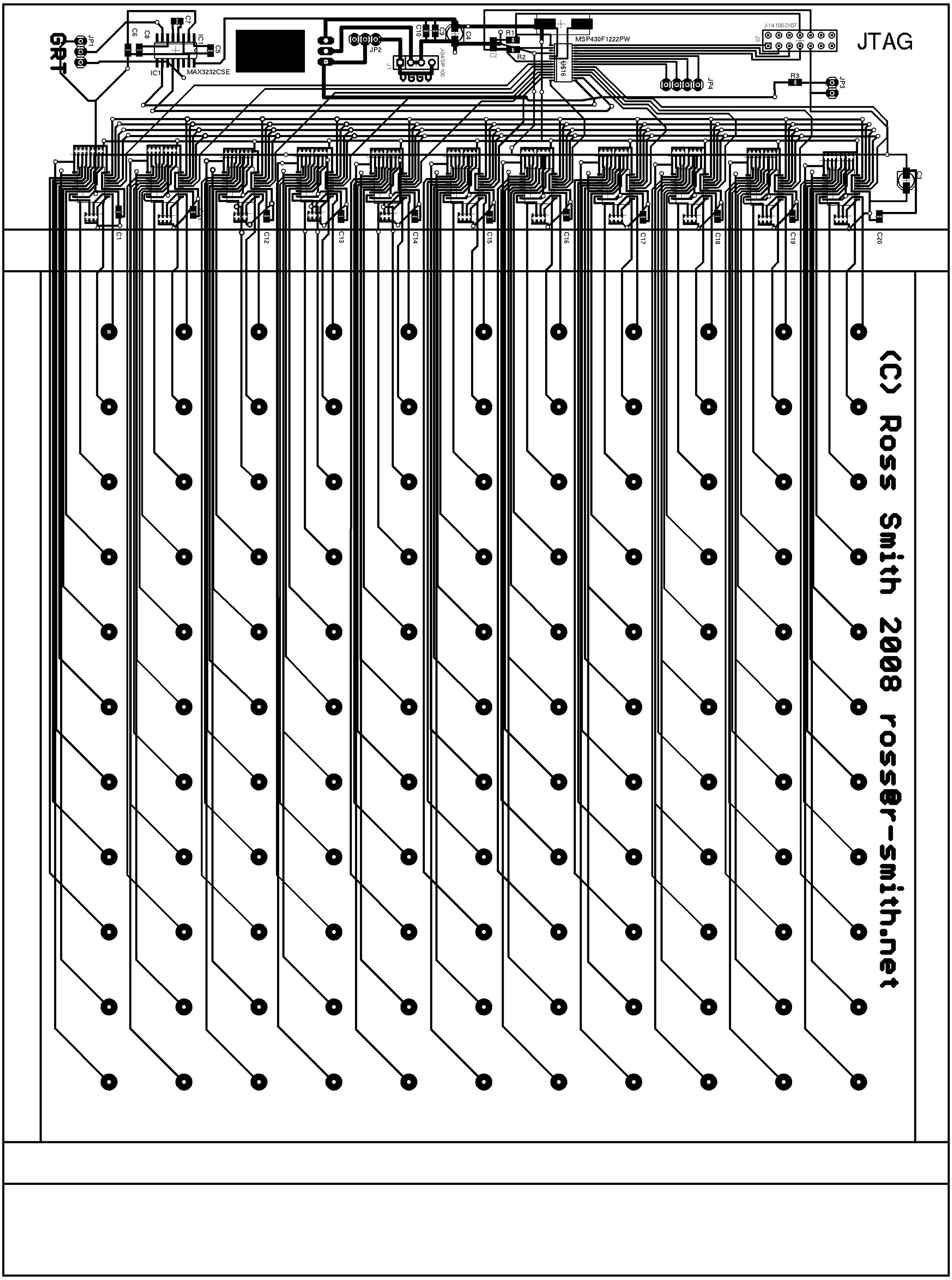
B

Digital Foam Schematics

The electrical schematics for each of the Digital Foam prototypes are very similar. The number of ADC chips used varies depending on the number of sensor attached, and the physical layout of the printed circuit board also varies. Provided below is the schematic and printed circuit board layout for version two of the Flat Digital Foam prototype.


MSP430F1222PW
MAX3232CSE
TLV1543
OUTPUT COMMON IN
CRYSTAL




JTAG
GRT
MAX3232CSE
MSP430F1222PW
IC1
JP1
JP2
JP3
JP4
R1
R2
R3
C1
C12
C13
C14
C15
C16
C17
C18
C19
C20
(C) Ross Smith 2008 ross@r-smith.net

C

Mechanical Finger Configuration Details

To support a configurable design, the mechanical finger developed for this dissertation supports user programmable paths. This section provides the G-code listings for the simple stroke and complex stroke used in the experiments described in Chapter 6. Finally the script used to provide a serial interface between the personal computer running the Mach 3 software and the controlling laptop is provided.

C.1 Simple stroke g-code listing

```
% (Filename: stroke.nc)
% (Date: 2/9/2008)

% Set the units to metric
G21 (Units: Metric)

% Go to the home position
M01
M98 P0900 L1

%Run the stroke command n times
M98 P1000 L50

% Go to the home position
M98 P0900 L1

% Finish program
M30

% Home Position
O0900
G01 Z10.000 F200.0
G01 X-1.0000 Y90.0000 F500.0
M01
M99

% Stroke Function
O1000
% Make sure we are at the home position for the stroke
G01 Z3.0 F800
G01 X-1.0000 Y90.0000 Z3.0000 F800.00

% Make sure we are at the home position for the stroke
G01 X0.000 Y90.0000 F600
```

```
G01 Z-8.0000
G01 X160.0000
G01 Z3.0000 F300.0
G01 X-1.0000 Y90.0 F800.0
M99
```

C.2 Complex stroke g-code listing

```
% (Filename: ComplexStroke.nc)
% (Date: 30/9/2008)

% Set the units to metric
%G21 (Units: Metric)

% Cancel any cutter compensation and use absolute co ordinates.
%G40 G90

% Go to the home position
M01
M98 P0900 L1

%Run the stroke command n times
M98 P1000 L65

% Go to the home position
M98 P0900 L1

% Finish program
M30

% Home Position
O0900
G01 Z10.000 F200.0
G01 X-1.0000 Y90.0000 F500.0
M01
```

```
M99

% Complex Stroke Function
O1000
% Make sure we are at the home position for the stroke
G01 Z3.0 F800
G01 X-1.0000 Y90.0000 Z3.0000 F800.00

%Move along half circles.
G01 X0.000 Y90.0000 F600
G01 Z-8.0000 F500
G02 X20.000 Y110.000 R20.000
G02 X40.000 Y90.000 R20.000
G03 X60.000 Y70.000 R20.00
G03 X80.000 Y90.000 R20.000
G02 X100.000 Y110.000 R20.000
G02 X120.000 Y90.000 R20.000
G03 X140.000 Y70.000 R20.00
G03 X160.000 Y90.000 R20.000
G01 Z4.0000 F400

M99
```

C.3 Serial interface to Mach3 software

```
'This script allows me to dump the current DRO values of the
'Mill to the serial port. The serial port baud rate and port
'can be set in the General Configuration menu.

'Loop endlessly writing the current DRO values to the serial
'port

While true
```

```
  If(GetOEMDRO(83) < 0) Then
    Call sendSerial ("NewStroke*")
  Else
    'Write the DRO values
    'If(GetOEMDRO(85) < 0) Then
      Call writeDROSerial()
    'End If
  End If

  'Sleep for a bit so we dont flood the serial port
  Sleep(200)
Wend

'Dump the DRO values out to the serial port with a * as the
'end line
Sub writeDROSerial()
  Call SendSerial (GetOEMDRO(83) & " " & GetOEMDRO(84) &
    " " & GetOEMDRO(85) & "*")
End Sub

'CPU sleep function, currently there is a bug using the built
'in sleep and I get lots of hangs so we use this for now.

Sub delay()
  Dim Count As Integer
  Count =0

  While Count < 10000
    Count = Count + 1
  Wend
End Sub
```

D

Conductive Foam Technical Information

One of the main materials used for the development of Digital Foam is the conductive foam material. The low density conductive foam material can be purchased from RS Components[1] with catalogue number 550-066. The technical suppliers information is provided below.

[1] www.rsaustralia.com

Wolfgang Warmbier
Systeme gegen Elektrostatik
♦ Untere Gießwiesen 21 ♦ 78247 Hilzingen ♦ Tel.: +49-7731-86880 ♦ Fax: +49-7731-868830

PU - Foam
(Part No.: 445x.W)

- Volume conductive
- Complies with EN 61340-5-1
- Open cells
- Soft
- **Colour:** Black

Physical properties:

	Standard	Typical values
Density	DIN EN 845	20 - 30 kg/m^3
Compression hardness	DIN 53577	3,2 kPa ± 15% (at 40%)
Tensile strength	DIN 53571	min. 100 kPa
Elongation at break	DIN 53571	min. 250 %
Residual compression set	(24h/70°C/50%)	< 10%
Temperature range	In-house test	-30°C to +100° C
Thickness		6 mm, 15 mm

Electrical properties:

	Test Standard	Typical values	Requirements
Surface resistance R_S	EN 61340-5-1 EN 61340-2-3	10^4 - 10^5 Ω	$10^2 \leq R_S \leq 10^5$ Ω EN 61340-5-1

E

Spherical Digital Foam Trial Study

A survey of questions was provided to each of the subjects during the trial study, the question sheet handed out is provided below.

DIGITAL FOAM MENU OPERATION QUESTIONNAIRE

Admin only:

ID:

Age: ______________ Gender: M F

Displaying (turning on) the menu on was	☐ Very Easy	☐	☐	☐	☐ Very Hard
Performing a click using Digital Foam was	☐ Very Easy	☐	☐	☐	☐ Very Hard
Selecting the correct menu item was	☐ Very Easy	☐	☐	☐	☐ Very Hard
I found the input device	☐ Too small	☐	☐	☐	☐ Too large
The rotation angle used to change to the next item was	☐ Too small	☐	☐	☐	☐ Too large
I found operating Menus with one hand	☐ Very Easy	☐	☐	☐	☐ Very Hard
I found operating Menus with two hands	☐ Very Easy	☐	☐	☐	☐ Very Hard
Overall I found the menu easy to use	☐ Strongly Agree	☐	☐	☐	☐ Strongly Disagree
Overall I could control the menu system	☐ Strongly Agree	☐	☐	☐	☐ Strongly Disagree
I would use the menu system with Digital Foam	☐ Strongly Agree	☐	☐	☐	☐ Strongly Disagree
	☐ 0	☐	☐	☐	☐ 5

What features do you like for the menu system?

How would you change the menu system?

What else do you think Digital Foam could be used for?

Other comments

F

Attachments

A number additional materials are provided to support this dissertation, these include videos and electronic documents. The information is provided on a CD-ROM created at the time of publication of this dissertation, while any new information will be provided on the internet.

F.1 CD-ROM

The attached CD-ROM provides electronic copies of the following materials:

- An electronic copy of this dissertation in portable document formant (PDF).
- An archive of all the current author publications to date (PDF).
- Videos demonstrating the use of both the Flat and Spherical Digital Foam input devices.

F.2 Internet

The research performed in this dissertation is project with ongoing developments. The latest information will be made available at http://r-smith.net and http://wearables.unisa.edu.au as it progresses. The author can be contacted at either ross@r-smith.net or ross@cs.unisa.edu.au.

Bibliography

[ALTY99] Alty, J. L., and Knott, R. P. Metaphor and human-computer interaction: a model based approach. pages 307–321, Berlin, 1999.

[AZUM01] Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., and MacIntyre, B. Recent advances in augmented reality. In Computer Graphics and Applications, IEEE, volume 21, pages 34–37, 2001.

[AZUM97] Azuma, R. A survey of augmented reality. In Presence: Teleoperators and Virtual Environments, volume 6, pages 355–385, 1997.

[BAEC95] Baecker, R. M., Grudin, J., Buxton, W. A. S., and Greenberg, S. Touch, gesture, and marking. In Human-computer interaction: toward the year 2000, pages 469–482, San Francisco, CA, 1995. Morgan Kaufmann Publishers Inc.

[BALA97] Balakrishnan, R., Baudel, T., Kurtenbach, G., and Fitzmaurice, G. The rockin'mouse: integral 3D manipulation on a plane. In CHI '97: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 311–318, Atlanta, GA, 1997.

[BALA99] Balakrishnan, R., Fitzmaurice, G., Kurtenbach, G., and Singh, K. Exploring interactive curve and surface manipulation using a bend and twist sensitive input strip. In I3D '99: Proceedings of the 1999 symposium on Interactive 3D graphics, pages 111–118, Atlanta, GA, 1999.

[BANK90] Banks, M., and Cohen, E. Real time spline curves from interactively sketched data. volume 24, pages 99–107, 1990.

[BLAS02] Blaskö, G., and Feiner, S. A menu interface for wearable computing. In 6th International Symposium on Wearable Computers (ISWC 2002), pages 164–165, seattle, WA, Oct 2002.

[BLUM02] Blum, R., Wilson, C., Hasler, P., and DeWeerth, S. A cmos imager with real-time frame differencing and centroid computation. volume 3, pages 329–332, 2002.

[BOOK05] Books, L. The figure in clay: Contemporary sculpting techniques by master artists. Sterling publishing Co., Inc., 2005.

[BOWM01] Bowman, D. A., Kruijff, E., LaViola, J. J., and Poupyrev, I. An introduction to 3-D user interface design. volume 10, pages 96–108, Cambridge, MA, USA, 2001. MIT Press.

[BRAD05] Brady, S., Diamond, D., and Lau, K.-T. Inherently conducting polymer modified polyurethane smart foam for pressure sensing. In Sensors and Actuators A: Physical, volume 119, pages 398–404, Apr 2005.

[BROO99] Brooks, F. P. What's real about virtual reality? volume 19, pages 16–27, Los Alamitos, CA, USA, 1999.

[BROW88] Brown, C. M. Human-computer interface design guidelines. Norwood, NJ, 1988. Ablex Publishing.

[BUXT07] Buxton, W. Multi-touch systems that i have known and loved. 2007.

[BUXT83] Buxton, W. Lexical and pragmatic considerations of input structures. volume 17, pages 31–37, 1983.

[BUXT86] Buxton, W. Chunking and phrasing and the design of human-computer dialogues. pages 475–480, 1986.

[BUXT90] Buxton, W. There's more to interaction than meets the eye: some issues in manual input. pages 122–137, Upper Saddle River, NJ, USA, 1990. Prentice Hall Press.

[CARD91] Card, S. K., Mackinlay, J. D., and Robertson, G. G. A morphological analysis of the design space of input devices. volume 9, pages 99–122, 1991.

[CARD94] Cardoz, C. Les realites virtuelles. Dominos, Flammarion, 1994.

[CHEN08] Cheng, K. Direct interaction with large displays through monocular computer vision. Oct 2008.

[COHE99] Cohen, J. M., Markosian, L., Zeleznik, R. C., Hughes, J. F., and Barzel, R. An interface for sketching 3D curves. In I3D '99: Proceedings of the 1999 symposium on Interactive 3D graphics, pages 17–21, Atlanta, GA, 1999.

[DEBE96] Debevec, P. E., Taylor, C. J., and Malik, J. Modeling and rendering architecture from photographs: A hybrid geometry- and image-based approach. In Proceedings of the 23rd annual conference on Computer graphics and interactive techniques, pages 11–20, New Orleans, LA, Aug 1996.

[DEER95] Deering, M. F. Holosketch: A virtual reality sketchin / animation tool. In ACM Transactions on Computer-Human Interaction, volume 2, pages 220–238, Sep 1995.

[DEME95] Dementhon, D. F., and Davis, L. S. Model-based object pose in 25 lines of code. volume 15, pages 123–141, 1995.

[DENN00] Dennerlein, J. T., Martin, D. B., and Hasser, C. Force-feedback improves performance for steering and combined steering-targeting tasks. In CHI '00: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 423–429, The Hague, The Netherlands, 2000.

[DIET01] Dietz, P., and Leigh, D. Diamondtouch: a multi-user touch technology. In Proceedings of the 14th annual ACM symposium on User interface software and technology, pages 219–226, Orlando, FL, 2001.

[DIPI08] Dipietro, L., Sabatini, A., and Dario, P. A survey of glove-based systems and their applications. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 38(4):461–482, July 2008.

[DORF01] Dorfmüller-Ulhaas, K., and Schmalstieg, D. Finger tracking for interaction in augmented environments. In ISAR '01: Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR'01), page 55, Washington, DC, USA, 2001. IEEE Computer Society.

[DUNN06] Dunne, L. E., Brady, S., Tynan, R., Lau, K., Smyth, B., Diamond, D., and O'Hare, G. M. P. Garment-based body sensing using foam sensors. In Proceedings of the 7th Australasian User interface conference, pages 165–171, Hobart, Australia, Jan 2006.

[ENGL67] English, W., Engelbart, D., and Berman, M. Display-selection techniques for text manipulation. volume HFE-8, pages 5–15, March 1967.

[FELF01] Felfernig, A., Friedrich, G., Jannach, D., and Zanker, M. Intelligent support for interactive configuration of mass-customized products. In IEA/AIE '01: Proceedings of the 14th International conference on Industrial and engineering applications of artificial intelligence and expert systems, pages 746–756, London, UK, 2001. Springer-Verlag.

[FISC03] Fischer, A., and Vance, J. M. Phantom haptic device implemented in a projection screen virtual environment. In EGVE '03: Proceedings of the workshop on Virtual environments 2003, pages 225–229, Zurich, Switzerland, 2003.

[FJEL09] Fjeld, M., and Barendregt, W. Epistemic action: A measure for cognitive support in tangible user interfaces. 41(3):876–881, 2009.

[FOLE84] Foley, J. D., Wallace, V. L., and Chan, P. The human factors of computer graphics interaction techniques. volume 4, pages 13–48, Los Alamitos, CA, USA, 1984.

[FOXL98a] Foxlin, E., Harrington, M., and Altshuler, Y. Miniature 6-DOF inertial system for tracking hmds. In SPIE Conference on Helmet- and Head-Mounted Displays, volume 3362, Orlando, FL, 1998.

[FROH00a] Fröhlich, B., and Plate, J. The cubic mouse a new device for three-dimensional input. In Proceedings of the SIGCHI conference on Human factors in computing systems, The Hague, The Netherlands, Apr 2000.

[FROH00b] Fröhlich, B. The quest for intuitive 3D-input devices. In HCI International, Las Vegas, NV, 2000.

[FROH06] Fröhlich, B., Hochstrate, J., Kulik, A., and Huchauf, A. On 3D input devices. In IEEE Computer Graphics and Applications, volume 26, pages 15–19, 2006.

[GALY91] Galyean, T. A., and Hughes, J. F. Sculpting: an interactive volumetric modeling technique. volume 25, pages 267–274, 1991.

[GERB04] Gerber, D., and Bechmann, D. Design and evaluation of the ring menu in virtual environments. In Immersive projection technologies, 2004.

[GERB05] Gerber, D., and Bechmann, D. The spin menu: a menu system for virtual environments. In IEEE Virtual Reality Conference, pages 271–272, 2005.

[GIBS77] Gibson, J. J. The theory of affordances.

[GIBS79] Gibson, J. J. The ecological approach to visual perception. 1979.

[GROS03] Grossman, T., Balakrishnan, R., and Singh, K. An interface for creating and manipulating curves using a high degree-of-freedom curve input device. In CHI '03: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 185–192, Ft. Lauderdale, FL, 2003.

[GROS04] Grossman, T., Wigdor, D., and Balakrishnan, R. Multi-finger gestural interaction with 3d volumetric displays. In UIST '04: Proceedings of the 17th annual ACM symposium on User interface software and technology, pages 61–70, Santa Fe, NM, 2004.

[GROS05] Grossman, T., Wigdor, D., and Balakrishnan, R. Multi-finger gestural interaction with 3D volumetric displays. In SIGGRAPH '05: ACM SIGGRAPH 2005 Papers, pages 931–931, Los Angeles, CA, 2005.

[HADD76] Haddad, A. Applied optimal estimation. volume 64, pages 574–575, April 1976.

[HANX05] Han, J. Y. Low-cost multi-touch sensing through frustrated total internal reflection. In UIST '05: Proceedings of the 18th annual ACM symposium on User interface software and technology, pages 115–118, Seattle, WA, 2005.

[HEND08] Henderson, S. J., and Feiner, S. Opportunistic controls: leveraging natural affordances as tangible user interfaces for augmented reality. In VRST '08: Proceedings of the 2008 ACM symposium on Virtual reality software and technology, pages 211–218, Bordeaux, France, 2008.

[HERN94] Herndon, K. P., van Dam, A., and Gleicher, M. The challenges of 3D interaction: a chi '94 workshop. volume 26, pages 36–43, 1994.

[HINC02] Hinckley, K., Cutrell, E., Bathiche, S., and Muss, T. Quantitative analysis of scrolling techniques. In CHI '02: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 65–72, Minneapolis, MN, 2002.

[HINC94] Hinckley, K., Pausch, R., Goble, J. C., and Kassell, N. F. Passive real-world interface for neurosurgical visualization. In Proceedings of the SIGCHI conference on Human factors in computing systems, pages 452–458, Boston, MA, Apr 1994.

[HINC98] Hinckley, K., Pausch, R., Proffitt, D., and Kassell, N. F. Two-handed virtual manipulation. 5(3):260–302, 1998.

[HINC99] Hinckley, K., Sinclair, M., Hanson, E., Szeliski, R., and Conway, M. The videomouse: a camera-based multi-degree-of-freedom input device. In UIST '99: Proceedings of the 12th annual ACM symposium on User interface software and technology, pages 103–112, Asheville, NC, 1999.

[HOLL93] Holloway, R., and Lastra, A. Virtual environments: A survey of the technology. Chapel Hill, NC, 1993.

[HOLM08] Holman, D., and Vertegaal, R. Organic user interfaces: designing computers in any way, shape, or form. volume 51, pages 48–55, 2008.

[IMME08] Immersion, C. Cyber gloves, Immersion Corporation, http://www.immersion.com. 2008.

[ISHI97] Ishii, H., and Ullmer, B. Tangible bits: towards seamless interfaces between people, bits and atoms. In CHI '97: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 234–241, Atlanta, GA, 1997.

[IWAT05] Iwata, H., Yano, H., and Ono, N. Volflex. In SIGGRAPH '05: ACM SIGGRAPH 2005 Emerging technologies, page 31, Los Angeles, CA, 2005.

[JOHN89] Johnson, J., Roberts, T., Verplank, W., Smith, D., Irby, C., Beard, M., and Mackey, K. The xerox star: a retrospective. volume 22, pages 11–26, 28–29, Sep 1989.

[JUNG04] Jung, H.-k., Nam, T.-j., Lee, H.-s., and Han, S.-y. Spray modeling: Augmented reality based 3D modeling interface for intuitive and evolutionary form development. In Proceedings of International Conference on Artifical Reality and Telexistence, Coex, korea, 2004.

[JUNG05] Jung, H.-k., Nam, T.-j., and Lee, H.-s. 3D modeling interface with air spray: Field study of 3D model making and prototype development. In Conference On Human Factors In Computing Systems, Portland, Oregon, Apr 2005.

[JUXX03] Ju, W., Madsen, S., Fiene, J., Bolas, M., McDowall, I., and Faste, R. Interaction devices for hands-on desktop design. In Proceedings of the SPIE/IS&T, pages 585–595, Santa Clara, CA, May 2003.

[KAMI04] Kamiyama, K., Kajimoto, H., Vlack, K., Kawakami, N., Mizota, T., and Tachi, S. Gelforce. In SIGGRAPH '04: ACM SIGGRAPH 2004 Emerging technologies, page 5, Los Angeles, CA, 2004.

[KATO99] Kato, H., and Billinghurst, M. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In 2nd Int'l Workshop on Augmented Reality, pages 85–94, San Francisco, Ca, Oct 1999.

[KATO99b] Kato, H., and Billinghurst, M. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In IWAR '99: Proceedings of the 2nd IEEE and ACM International Workshop on Augmented Reality, page 85, Washington, DC, USA, 1999.

[KEIJ07] Keijser, J., Carpendale, S., Hancock, M., and Isenberg, T. Exploring 3D interaction in alternate control-display space mappings. pages 17–24, Charlotte, NC, March 2007.

[KENN97] Salisbury, J. K., and Srinivasan, M. A. Phantom-based haptic interaction with virtual objects. volume 17, pages 6–10, Los Alamitos, CA, USA, 1997.

[KOJI06] Kojima, M., Sugimoto, M., Nakamura, A., Tomita, M., Nii, H., and Inami, M. Augmented coliseum: an augmented game environment with small vehicles. pages 6 pp.–, Jan. 2006.

[KOLL96] Koller, D. R., Mine, M. R., and Hudson, S. E. Head-tracked orbital viewing: An interaction technique for immersive virtual environments. In The 28th Intl. Conference on Computer Graphics and Interactive Techniques, pages 81–82, Seattle, WA, 1996.

[KRUE85] Krueger, M. W., Gionfriddo, T., and Hinrichsen, K. Videoplace–an artificial reality. volume 16, pages 35–40, 1985.

[KRUG94] Kruger, W., and Fröhlich, B. The responsive workbench. In IEEE Computer Graphics and Applications, volume 14, pages 12–15, 1994.

[KRYX06] Kry, P. G., and Pai, D. K. Interaction capture and synthesis. volume 25, pages 872–880, 2006.

[KULI06] Kulik, A., Blach, R., and Fröhlich, B. "two - 4 - six" - a handheld device for 3D-presentations. In IEEE Symposium on 3D User Interfaces, pages 167–170, Washington, DC, Mar 2006.

[LAKO80] Lakoff, G., and mark Johnson. Metaphors we live by. 1980.

[LAMO94] Lamousin, H., and Waggenspack, N.N., J. Nurbs-based free-form deformations. volume 14, pages 59–65, Nov 1994.

[LECL07] LeClerc, V., Parkes, A., and Ishii, H. Senspectra: a computationally augmented physical modeling toolkit for sensing and visualization of structural strain. In CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 801–804, San Jose, CA, 2007. ACM.

[LECU00] Lecuyer, A., Coquillart, S., Kheddar, A., Richard, P., and Coiffet, P. Pseudo-haptic feedback: Can isometric input devices simulate force feedback? In VR '00: Proceedings of the IEEE Virtual Reality 2000 Conference, page 83, Washington, DC, USA, 2000.

[LEEX04] Lee, C.-H. J., Selker, T., Precher, E., and Gens, R. isphere: a proximity-based 3D input device. In SIGGRAPH, 2004.

[LEEX05] Lee, C.-H. J., Hu, Y., and Selker, T. isphere: a proximity-based 3D input interface. In Proceedings of CAAD Futures, Vienna, Austria, 2005.

[LEEX06] Lee, C.-H. J., Hy, Y., and Selker, T. isphere:a free-hand 3D modelling interface. volume 4, 2006.

[LEGA98] Leganchuk, A., Zhai, S., and Buxton, W. Manual and cognitive benefits of two-handed input: an experimental study. volume 5, pages 326–359, 1998.

[LIAN93] Liang, J., and Green, M. Geometric modeling using six degrees of freedom input devices. In 3rd Int'l Conference on CAD and Computer Graphics, pages 217–222, 1993.

[MACK90] Mackinlay, J., Card, S. K., and Robertson, G. G. A semantic analysis of the design space of input devices. volume 5, pages 145–190, Hillsdale, NJ, USA, 1990. L. Erlbaum Associates Inc.

[MASS94] Massie, T. H., and Salisbury, J. K. The phantom haptic interface: A device for probing virtual objects. In ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov 1994.

[MAZZ04] Mazzone, A., Spagno, C., and kunz, A. Morphing the smartmesh: Proposing a novel control architecture. pages 467–472, Munich, Germany, 2004.

[MCDO01] McDonnell, K. T., Qin, H., and Wlodarczyk, R. A. Virtual clay: a real-time sculpting system with haptic toolkits. In I3D '01: Proceedings of the 2001 symposium on Interactive 3D graphics, pages 179–190, 2001.

[MCVI56] McVicker, N. W., and McVicker, J. S. Patent: 3,167,440. 1956.

[MEHT82] Mehta, N. A flexible machine interface. 1982.

[MICH02] Michelitsch, G., van Veen, H. A., and van Erp, J. B. F. Multi-finger haptic interactions within the miamm project. Edinburgh, UK, 2002.

[MILC06] Milczynski, M., Hermann, T., Bovermann, T., and Ritter, H. A malleable device with applications to sonification-based data exploration. In Proceedings of the 12th Meeting of the International Conference on Auditory Display, Queen Mary, London, Jun 2006.

[MITO06] Mitobe, K., Kaiga, T., Yukawa, T., Miura, T., Tamamoto, H., Rodgers, A., and Yoshimura, N. Development of a motion capture system for a hand using a magnetic three dimensional position sensor. In SIGGRAPH '06: ACM SIGGRAPH 2006 Research posters, page 102, Boston, Massachusetts, 2006.

[MURA94] Murakami, T., and Nakajima, N. Direct and intuitive input device for 3-d shape deformation. In CHI '94: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 465–470, Boston, MA, 1994.

[NECH99] Nechvatal, J. Immersive ideals / critical distances: A study of the affinity between artistic ideologies based in virtual reality and previous immersive idioms. In Ph.D Thesis, 1999.

[NIGR92] Nigrosh, L. I. Sculpting clay. Worcester, Massachusetts, 1992. Davis publications Inc.

[NORM07] Norman, D. The design of future things. New York, Basic Books, 2007.

[NORM88] Norman, D. The design of everyday things.

[PAIX05] Pai, D. K., VanDerLoo, E. W., Sadhukan, S., and Kry, P. G. The Tango: A tangible tangoreceptive whole-hand human interface. In Proceedings of World-Haptics (Joint Eurohaptics Conference and IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems), Pisa, Italy, March 18-20, 2005.

[PIEK02b] Piekarski, W., and Thomas, B. Using artoolkit for 3D hand position tracking in mobile outdoor environments. 2002.

[PIEK04b] Piekarski, W., and Thomas, B. H. Augmented reality working planes: A foundation for action and construction at a distance. In Proceedings of the Third IEEE and ACM International Symposium on Mixed and Augmented Reality, pages 162–171, Arlington, VA, Oct 2004.

[PIEK06a] Piekarski, W., and Smith, R. Robust gloves for 3D interaction in mobile outdoor ar environments. In International Symposium on Mixed and Augmented Reality, Santa Barbara, Ca, Oct 2006.

[PIHU08] Pihuit, A., Kry, P., and Cani, M.-P. Hands on virtual clay. pages 267–268, June 2008.

[PINT08] Pintaric, T., and Kaufmann, H. A rigid-body target design methodology for optical pose-tracking systems. In VRST '08: Proceedings of the 2008 ACM symposium on Virtual reality software and technology, pages 73–76, Bordeaux, France, 2008.

[POIN08] Research, P. G. Technical application note tan2008005: Stereo vision introduction and applications. 2008.

[POLH07] Polhemus. Fastscan, http://www.polhemus.com, 2007.

[RAAB79] Raab, F., Blood, E., Steiner, T., and Jones, H. Magnetic position and orientation tracking system. volume AES-15, pages 709–718, Sept. 1979.

[RASM96] Rasmussen, C., Toyama, K., and Hager, G. D. Tracking objects by color alone. New Haven, CT, 1996.

[REIT05] Reitmayr, G., Chiu, C., Kusternig, A., Kusternig, M., and Witzmann, H. iorb - unifying command and 3D input for mobile augmented reality. In 3D User Interfaces, Bonn, Germany, Mar 2005.

[RGBZ08] Bamji, C. Us patent 7375803 - rgbz (red, green, blue, z-depth) filter system usable with sensor systems, including sensor systems with synthetic mirror enhanced three-dimensional imaging. 2008.

[SAGA07] Saga, S., Kuroki, S., Kawakami, N., and Tachi, S. Fibratus tactile sensor using reflection on an optical lever. In SIGGRAPH '07: ACM SIGGRAPH 2007 emerging technologies, page 3, San Diego, CA, 2007.

[SAGE71] Sage, G. H. Introduction to motor behavior: a neuropsychological approach. 1971.

[SCHK01] Schkolne, S., Pruett, M., and Schröder, P. Surface drawing: creating organic 3D shapes with the hand and tangible tools. In Proceedings of the SIGCHI conference on Human factors in computing systems, pages 261–268, Seattle, WA, 2001.

[SEAR03] Sears, A., and Jacko, J. A. The human-computer interaction handbook: Fundamentals, evolving technologies and emerging applications. In Second Edition, 2003.

[SEDE86] Sederberg, T. W., and Parry, S. R. Free-form deformation of solid geometric models. volume 20, pages 151–160, 1986.

[SHNE86] Shneiderman, B. Designing the user interface: strategies for effective human-computer interaction. Boston, MA, USA, 1986. Addison-Wesley Longman Publishing Co., Inc.

[SHOE92] Shoemake, K. Arcball: a user interface for specifying three-dimensional orientation using a mouse. In Proceedings of the conference on Graphics interface '92, pages 151–156, Vancouver, British Columbia, Canada, 1992. Morgan Kaufmann Publishers Inc.

[SMIT07a] Smith, J., Graham, T., Holman, D., and Borchers, J. Low-cost malleable surfaces with multi-touch pressure sensitivity. pages 205–208, Oct. 2007.

[SMIT08b] Smith, R. T., Thomas, B. H., and Piekarski, W. Tech note: Digital foam. pages 35–38, March 2008.

[SMIT08d] Smith, R. T., Thomas, B. H., and Piekarski, W. Digital foam interaction techniques for 3D modeling. In VRST '08: Proceedings of the 2008 ACM symposium on Virtual reality software and technology, pages 61–68, Bordeaux, France, 2008.

[SMIT09] Smith, R. T., Thomas, B. H., and Piekarski, W. Digital foam us patent application number: 12/381147. 2009.

[SOWI93] Sowizral, H. A., and Barnes, J. C. Tracking position and orientation in a large volume. pages 132–139, Sep 1993.

[SPAT08] Spatial Freedom. Spatial controllers (3D motion controllers). 2008.

[SUND01] Sundin, M. Elastic computer input control in six degrees of freedom. Switzerland, 2001.

[SUND09] Sundin, M., and Fjeld, M. Softly elastic 6dof input. 2009.

[SUTH65] Sutherland, I. E. The ultimate display. In IFPI Congress, pages 506–508, 1965.

[VLAC05] Vlack, K., Mizota, T., Kawakami, N., Kamiyama, K., Kajimoto, H., and Tachi, S. Gelforce: a vision-based traction field computer interface. In CHI '05: CHI '05 extended abstracts on Human factors in computing systems, pages 1154–1155, Portland, OR, 2005.

[VOGT04] Vogt, F., Chen, T., Hoskinson, R., and Fels, S. A malleable surface touch interface. In SIGGRAPH '04: ACM SIGGRAPH 2004 Sketches, page 36, Los Angeles, CA, 2004.

[WAGN02] Wagner, C. R., Howe, R. D., and Stylopoulos, N. The role of force feedback in surgery: Analysis of blunt dissection. In HAPTICS '02: Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, page 73, Washington, DC, USA, 2002.

[WELC02] Welch, G., and Foxlin, E. Motion tracking: no silver bullet, but a respectable arsenal. volume 22, pages 24–38, Nov.-Dec. 2002.

[WELC92] Welch, W., and Witkin, A. Variational surface modeling. In SIGGRAPH '92: Proceedings of the 19th annual conference on Computer graphics and interactive techniques, pages 157–166, 1992.

[WELL91] Wellner, P. The digitaldesk calculator: Tangible manipulation on a desk top display. In Proceedings of UIST'92, the ACM Symposium on User Interface Software and Technology, pages 107–115, 1991.

[WIGD06] Wigdor, D., Shen, C., Forlines, C., and Balakrishnan, R. Effects of display position and control space orientation on user preference and performance. In Proceedings of the SIGCHI conference on Human Factors in computing systems, pages 309–318, Montréal, Québec, Canada, 2006.

[WILL03] Williams, J., and Michelitsch, G. Designing effective haptic interaction: inverted damping. In CHI '03: CHI '03 extended abstracts on Human factors in computing systems, pages 856–857, Ft. Lauderdale, FL, 2003.

[WOO98] Woo, M., Neider, J., and Davis, H. Opengl programming guide, second edition, the official guide to learning open gl, version 1.1. 1998.

[ZHAI04] Zhai, S. Mouse. In Encyclopedia of Human-Computer interaction, 2004.

[ZHAI93a] Zhai, S., Milgram, P., and Drascic, D. An evaluation of four 6 degree-of-freedom input techniques. In CHI '93: INTERACT '93 and CHI '93 conference companion on Human factors in computing systems, pages 123–125, Amsterdam, The Netherlands, 1993.

[ZHAI93b] Zhai, S., and Milgram, P. Human performance evaluation of manipulation schemes in virtual environments. pages 155–161, Sep 1993.

[ZHAI93c] Zhai, S. Investigation of feel for 6dof inputs: isometric and elastic rate control for manipulation in 3D environments. In Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Seattle, WA, 1993.

[ZHAI95] Zhai, S. Human performance in six degree of freedom input control. In Ph.D Thesis, University of Toronto, 1995.

[ZHAI96] Zhai, S., Milgram, P., and Buxton, W. The influence of muscle groups on performance of multiple degree-of-freedom input. In CHI '96: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 308–315, Vancouver, British Columbia, Canada, 1996.

[ZHAI97] Zhai, S., Smith, B. A., and Selker, T. Improving browsing performance: A study of four input devices for scrolling and pointing tasks. In INTERACT '97: Proceedings of the IFIP TC13 Interantional Conference on Human-Computer Interaction, pages 286–293, London, UK, UK, 1997. Chapman & Hall, Ltd.

[ZHAI99] Zhai, S., and Smith, B. A. An experimental study of document scrolling methods. In IBM Systems Journal, pages 642–651, 1999.

[ZHOU08] Zhou, H., and Hu, H. Human motion tracking for rehabilitation–a survey. volume 3, pages 1 – 18, 2008.