VIRTUAL SCULPTING WITH ADVANCED GESTURAL INTERFACE

A THESIS

SUBMITTED TO THE DEPARTMENT OF COMPUTER ENGINEERING

AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE

OF BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By

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August, 2013

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

VIRTUAL SCULPTING WITH ADVANCED GESTURAL INTERFACE

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In this study, we propose a virtual reality application that can be utilized to design preliminary/conceptual models similar to real world clay sculpting. The proposed system makes use of the innovative gestural interface that enhances the experience of the human-computer interaction. The gestural interface employs advanced motion capture hardware namely data gloves and six-degrees-of-freedom position tracker instead of classical input devices like keyboard or mouse. The design process takes place in the virtual environment that contains volumetric deformable model, design tools and a virtual hand that is driven by the data glove and the tracker. The users manipulate the design tools and the deformable model via the virtual hand. The deformation on the model is done by stuffing or carving material (voxels) in or out of the model with the help of the tools or directly by the virtual hand. The virtual sculpting system also includes volumetric force feedback indicator that provides visual aid. We also offer a mouse like interaction approach in which the users can still interact with conventional graphical user interface items such as buttons with the data glove and tracker. The users can also control the application with gestural commands thanks to our real time trajectory based dynamic gesture recognition algorithm. The gesture recognition technique exploits a fast learning mechanism that does not require extensive training data to teach gestures to the system. For recognition, gestures are represented as an ordered sequence of directional movements in 2D. In the learning phase, sample gesture data is filtered and processed to create gesture recognizers, which are basically finite-state machine sequence recognizers. We achieve real time gesture recognition by these recognizers without needing to specify gesture start and end points. The results of the conducted user study show that the proposed method is very promising in terms of gesture detection and recognition performance (73% accuracy) in a stream of motion. Additionally, the assessment of the user attitude survey denotes that the gestural interface is very useful and satisfactory. One of the novel parts of the proposed approach is that it gives users the freedom to create gesture commands according to their preferences for selected tasks. Thus, the presented gesture recognition approach makes the human-computer interaction process more intuitive and user specific.

Keywords: virtual sculpting, virtual clay potterry, volumetric deformation, virtual reality, dynamic gesture recognition, gesture detection, finite state machine-based recognition, gestural interfaces, gesture-based interaction.

ÖZET

EL HAREKETLERİNE DAYALI GELİŞMİŞ ARAYÜZ İLE SANAL MODELLEME

Nurettin Çağrı Kılıboz
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Ağustos, 2013

Bu çalışmada, gerçek dünya heykeltraşlığına benzeyen ön / kavramsal modelleri tasarlamak için kullanılabilir bir sanal gerçeklik uygulaması sunuyoruz. Önerilen sistem, insan-bilgisayar etkileşimi deneyimi artıran yenilikçi bir işaret tabanlı arayüz kullanmaktadır. İşaret tabanlı arayüz, el ve parmak hareketleri yakalamak için, klasik girdi aygıtları olan fare ve klavye yerine, veri eldiven ve altı derece serbestlikte veri toplayan bir manyetik konum izleyicilerden faydalanmaktadır. Tasarımlar; hacimce deforme edilebilir model, tasarım araçları ve sanal el içeren bir sanal ortamda gerçekleştirilmektedir. Sanal tasarım ortamında yer alan bu sanal el, veri eldiven ve pozisyon izleyici sayesinde kullanıcının el hareketlerini taklit ederek yönlendirilmektedir. Sistem, kullanıcıların tasarım araçları ve sanal el yardımıyla deforme edilebilir modeli işleyerek şekil vermesine olanak tanımaktadır. Model üzerinde deformasyon, tasarım araçları veya doğrudan sanal el ile, modele dışardan malzeme (hacim hücreleri) doldurma veya modelden malzeme oyularak yapılmaktadır. Tasarım sürecinde sistem "kuvvet geribildirim göstergesi" sayesinde kullanıcılara görsel yardım sağlamaktadır. Ayrıca kullanıcılar, veri eldiveni ve pozisyon izleyiciyi tarafından yönlendirilen el faresi ile geleneksel grafik kullanıcı arayüzü öğeleri ile etkileşime girebilmektedirler. Kullanıcılar aynı zamanda gerçek zamanlı yörünge tabanlı el hareket/jest tanıyan algoritma sayesinde uygulamayı kontrol edebilmektedirler. Sunulan el hareketi tanıma tekniği, kapsamlı ve büyük eğitim verilerine ihtiyaç duymadan, sisteme yeni hareketler öğretmeye olanak sağlamaktadır. Sunulan teknikte, el hareketleri, iki boyutlu yönlü hareketlerin sıralı dizisi olarak temsil edilir. Öğrenme aşamasında, sisteme sunulan örnek jestler/el hareketleri filtrelenerek işlenir. Daha sonra bu işlenmiş veri birer sonlu durum makinesi dizi tanıyıcıları olan el hareketi tanıyıcı makinaları oluşturmak için kullanılmaktadır. El hareketleri, jestlerin başlangıç ve bitiş noktaları belirtmeye gerek kalmadan bu tanıyıcılar tarafından gerçek zamanlı olarak sistem tarafından tanınabilmektedirler. Tez kapsamında yapılan kullanıcı çalışmasının sonucunda, önerilen yöntem, sürekli bir hareket akışı içerisinde belirli el hareketlerini/jestleri % 73 doğruluk ile algılama ve tanıma performansı göstermiştir. Ayrıca kullanıcı tutum anketinin sonuçlarına göre, işaret tabanlı arayüz kullanıcılar tarafından çok yararlı ve tatmin edici bulunmuştur. Önerilen yaklaşımın en önemli faydalarından biri de kullanıcıların seçilen görevler için kendi tercihlerine göre hareket komutları oluşturma özgürlüğü veriyor olmasıdır. Böylece, sunulan jest tanıma yaklaşımı insan-bilgisayar etkileşim sürecini daha sezgisel ve kullanıcıya özel hale getirmektedir.

Anahtar sözcükler: sanal modelleme, sanal çömlekçilik, hacimsel deformasyon, sanal gerçeklik, dinamik el hareketi tanıma, el hareketi tespiti, sonlu durum makinası tabanlı tanıma, işaret tabanlı arayüzler, işaret tabanlı etkileşim.

Acknowledgement

This thesis is the end of my journey in obtaining my M.S degree. At the end of this journey, I would like to thank all people, who made this thesis possible.

My first debt of gratitude must go to my advisor, Assoc. Prof. Uğur Güdükbay. Without his guidance and help, I would not finish this thesis. I would also like to thank to Assist. Prof. Dr. Tolga Çapın and Assoc. Prof. Dr. Sinan Gezici for reviewing and commenting on this thesis.

I would like to thank to the Scientific and Technological Research Council of Turkey (TÜBİTAK) for providing financial assistance during my study, through BİDEB program.

I also need to thank to the dear employees (especially Murat Özkan) of I.T. Department of Ministry of Economy. With their support and permission, I did have time to complete my work.

I really appreciate the help of my friends Can Koyuncu, Ersin Yümer, Fatma Güney, Murat Arar and Oğuz Yılmaz. During the hardest times of my study, they were there to support me. I could not complete my work without their invaluable and friendly assistance.

I owe my deepest gratitude to my parents, Cuma and Mübeccel Kılıboz, and my brother, Tuğrul. Their love, support and encouragement provided my inspiration and were my driving force.

Lastly, my special thanks goes to my beloved wife Duygu Sinem. Her informal support, sacrifice and encouragement has been indispensable. I feel very lucky to have a valuable life partner like her.

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Chapter 1

Introduction

Virtual reality is a computer-simulated environment that tries to achieve life-like experience of real world. Although the concept of virtual reality (VR) is very old, the realization and creations of complex virtual worlds that imitate the real one became possible only after the improvements in the computer hardware capabilities. VR applications accomplish this difficult task thanks to these advanced hardware devices that can provide realistic sensory information. For most of the VR applications, the primary target is to provide visual experience via special stereoscopic displays, while the others may include additional sensory information such as audio. Today, even tactile feedback is available via haptic output devices.

The main reasons behind the popularity of the VR applications is that it has various practical usage areas such as training, gaming, entertainment and modeling. Virtual sculpting is one of these branches which simulates the process of designing models similar to real world clay or wood sculpting [1]. In other words, virtual sculpting applications create a virtual environment and allow users to manipulate and deform the design objects in the way they want in this virtual environment.

Developments in the technology also contribute to the human-computer interaction (HCI) approaches. Various HCI studies have been proposed in the last few decades as an alternative to the classic input devices of keyboard and mouse. However, these new techniques have not been able to supersede the old ones due to their lack of intuitiveness. Additionally, their poor performance prevents them from being be practical. However, the cutting edge technologies especially touch operated devices such as kiosks, tablet PCs re-defined the whole HCI approaches. More intuitive and natural computer interfaces become the part of our daily lives. Gestural interfaces also play a crucial role among these interfaces because our hands are the main means to interact with our environment. Therefore, interaction approaches that makes use of this phenomenon naturally becomes a strong alternative the conventional ones.

1.1 Motivation and Contribution

1.1.1 Virtual Sculpting

In this study, we try to accomplish a virtual sculpting tool that can be used to design preliminary/conceptual models. The general advantage of all digital modeling tools is that it removes the physical barriers of the real world sculpting. Some of them, among many advantages, can be listed as follows: being able to undo the work you have done, collaborative work without being in the same presence, saving physical effort, being able to do tasks that are not physically possible, and so on.

With digital modeling tools, while gaining these advantages, we loose two of the most critical elements of the creative design process: naturalness and intuitiveness. Because many of CAD (Computer Aided Design) tools rely on the classical input devices like mouse and keyboard, they often cannot provide means for intuitive interaction [2]. The first basic advantage of our virtual sculpting tool is that it grants intuitiveness. Therefore, designing new models with the tool becomes an easy and natural task that does not require long term training or proficiency [3].

Conceptual design also known as preliminary design is the initial phase of a design process that aims the capture the essential form or shape of the product [4]. Frequently, it contains conceptual and artistic aspect of the desired model in a roughly detailed format. In most of the cases, conceptual design is made by skilled artists in the form of hand drawn sketch or clay model. Later, these sketches and clay models are interpreted and conveyed to a CAD application for production by another person who is well-trained and capable of using advanced CAD application. The major drawback of the traditional method is time and effort wasted for this transaction. One way of overcoming this drawback is to train conceptual design artist about how to use advanced CAD applications. However, most of the CAD applications require serious training and skills. Additionally, many of these artists are not as comfortable as when they do it on the sketch or clay model. The solution to this problem is the proposed virtual sculpting tool in which concept artists can design their models easily and naturally by means of virtual hand that mimics the artist hand movements in virtual design environment. With this method, artists can design models in a more intuitive manner without learning advanced CAD applications.

1.1.2 Gestural Interface

The other important contribution of our study is the proposed gestural interface. Our simple yet powerful gesture recognition algorithm can effectively detect and recognize dynamic hand gestures from a continuous hand motion. The recognition rates of the approach are sufficiently high to be used as alternative HCI technique. The attitude assessment of the user study also supports this claim with very high evaluation scores.

Because the presented gesture recognition algorithm does not require extensive data to learn new gestures, users can teach new gestures by performing a few sample gestures. This ability makes the user form their own gesture vocabulary to command the application or device without much effort. This feature also improves the quality of the interaction and makes the whole HCI experience more intuitive and user specific.

Although we utilize advanced motion capture hardware for our trajectory based gesture recognition algorithm, it is also applicable to more common and cheaper motion capture methods such as Microsoft Kinect^{TM} or Nintendo Wii^{TM} due to its gesture representation scheme. Computer vision based motion capture or inertial approaches are other feasible alternatives for the proposed algorithm. Additionally, the presented gesture recognition approach can be applied to other applications and devices such as computer games, video and music players that can be commanded with gestural interfaces. As a consequence, we can claim that our interaction technique is suitable for wide range of applications from different disciplines and research areas.

1.2 Overview of System Components

In order to create preliminary designs or artistic conceptual models, we propose a virtual reality based method in which users can modify virtual objects by means of virtual hand and/or virtual tools. The proposed method tries to simulate real life clay modeling techniques to achieve this task. The virtual design environment contains the following elements (see Figure 1.1):

Virtual Hand: It is a 3D hand mesh model controlled by the data glove and the position tracker. It is the primary means to interact with other objects in the virtual environment. It mimics the user's hand gestures and movements.

*Deformable Object:*It is the model that is being designed. It has a volumetric structure and consists of volume elements called voxels. Users can deform the virtual deformable object by adding/removing voxels with the help of deformation tools or virtual hand.

Deformation Tools: These tools are manipulated with the virtual hand or directly with the position trackers and used to carve/stuff voxels to the deformable objects. They may vary in the shape and size so that users can deform the model in the way they desire.

Virtual Hand User Interface: It constitutes the user interface part of the application. It consists of hand buttons which can be clicked by the virtual hand. It is used to control and direct the application as a classical user interface does.

Gestural Interface: It is the alternative approach to interact with the application. The users can command the system by performing trajectory based hand gestures. It allows users to direct the application in a natural and intuitive manner.

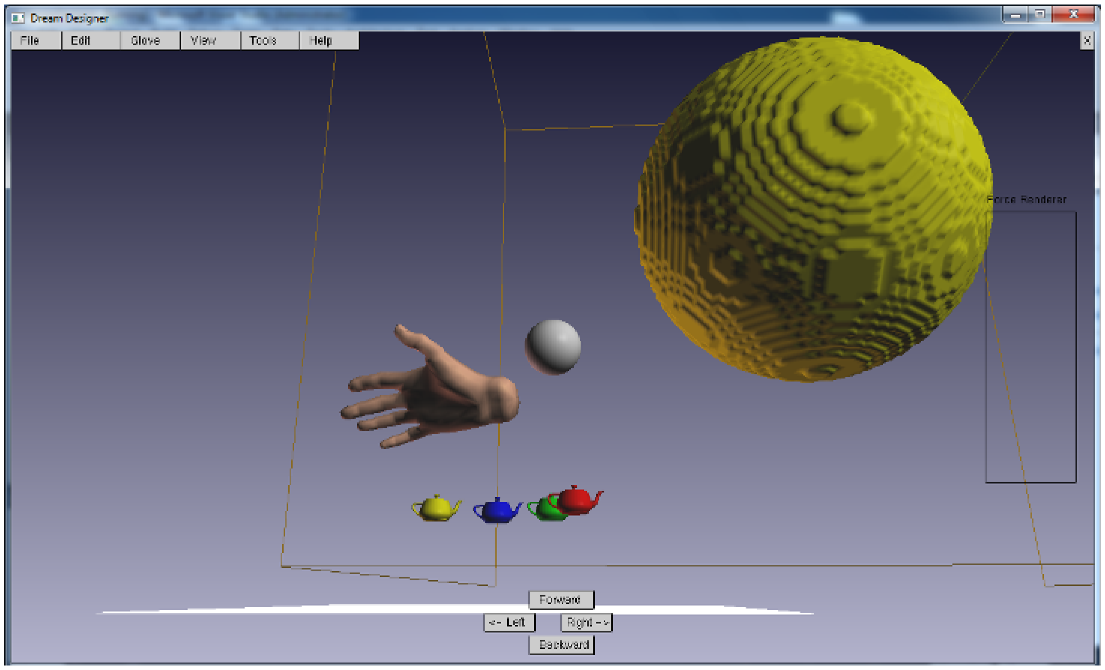


Figure 1.1: Overview of the virtual environment.

1.3 Software Development and Test Environment

The proposed system is developed and tested in a standard level personal computer whose specifications are as follows:

Processor: Intel ® Core ™ 2 Duo CPU (T6600 2.2GHz)

Memory (RAM): 3 GB

Operating System: Windows 7 SP1 (32 bit)

The program source code is written in C++ for efficiency. The selected integrated development environment (IDE) is Microsoft Visual Studio 2010. In order to render the virtual environment, OpenGL ^{TM} Graphic Library (Version 3.3.0) with GLUT is utilized.

1.4 Outline

The outline of the thesis as follows. In Chapter 2, we define the related concepts and give the detailed information about the existing approaches from literature. In Chapter 3, we describe the used motion capture approaches in detail. In Chapter 4, we give the details of the modification algorithms. Chapter 5 explains the innovative gestural interface approach in detail. In Chapter 6, we present the details and the results of the conducted user study. Finally, in Chapter 7, we lay out conclusion and future research directions of our study.

Chapter 2

Background

2.1 Computer-Aided Design

Computer-Aided Design (CAD) is defined as "use of computer systems to assist in the creation, modification, analysis, or optimization of a design" [5]. To be able to use computers in design procedure, computer software that enables users to produce technical drawings has been developed. CAD software makes use of different structures to represent designed model and support modification operations. Most widely used approaches used in today's CAD applications are Non-uniform Rational Basis Spline (NURBS), Bézier curves, volumetric representations and 3D mesh structures [5]. Outputs of CAD applications, in addition to the fine details, may also convey information about materials, dimension of designed models etc.; hence, manufacturing the models become feasible.

2.2 Virtual Sculpting

Although traditional CAD systems have been very productive for new product design, they are not suited to support conceptual design activities because these activities often require a more natural and intuitive mode of human-computer interaction [2]. For this reason, many researchers including industrial designers, engineers and artists search for innovative tools that can ease the conceptual design process and improve the naturalness of human-computer interaction for new product concepts. In order to overcome the communication problems that prevail in conventional CAD applications, virtual reality applications for conceptual prototyping are introduced in various studies [2, 6]. The key consequence of these studies is that human computer interaction approach used in the application must be intuitive to the user. Additionally, it should provide visual, tactile and audio feedback with the means of modern equipment such as stereoscopic displays, force renderers and stereo sound systems.

Even though the recent progress in technology provides the means for advanced VR applications, there are still some limitations. The first major bottleneck is the real time rendering of the complex world. When collision detection and physical properties of the virtual models are included for realism, achieving online simulation rates become even more difficult for complex virtual environments [7]. The other drawback of the existing VR system is that they require high-end electronic devices. These devices often are financially costly and difficult to obtain.

In the early stages of the VR applications, the models are initially designed in conventional CAD applications and then transferred to the VR systems for 3D visualization, thanks to head-mounted displays and goggles [8, 9]. Later, many VR based CAD systems that allow user to design the models in the VR environment start to appear in the literature. These systems [4, 10, 11] make use of the advanced interaction approaches such as voice commands, gestural interfaces, 3D rendering or haptic feedback devices. The potential and limitations of the VR applications highly depend on the selected HCI approach. For example, voice based interaction is superior to the gesture-based interaction because it enables user to freely move his/her hands but it has the disadvantage of poor recognition performance [2].

Virtual modeling (sculpting) tools can also be classified according to the model representation and deformation techniques. The earliest studies in this field focus on constructive solid geometry (CSG)based modification such as boolean operation on geometric primitives [12]. Some of the studies [13, 14] use voxel based representation similar to our work while the others prefer surface based data structures which can be deformed using B-spline [15], mass-spring [16] techniques. There are also studies that combine the surface and volume based approaches like subdivision solids [17]. The deformation approach also changes according the chosen representation. Volumetric representation is more suitable for volumetric deformation such as stuffing and carving while physics-based deformations are more suited for mass-spring and B-spline models [7].

2.3 Motion Capture

Although virtual environments create a realistic image of the real world, users still need to use classic computer input devices such as mouse and keyboard to interact with the virtual environments which cause users to lose intuitiveness [18]. To address this problem, different human-computer interaction devices that can capture human hand motion data are introduced. One of the commonly used input devices for this purpose are data gloves. Although various glove models exist, data gloves are generally wearable electronic devices that are capable of collecting the bending values of finger joints with different number of sensors of various types. Because most of the data gloves collect only the bending angles, additional information, namely hand position and orientation are required to fully simulate the real hand movements. For this purpose, 3D position and orientation trackers that utilize different technologies, such as magnetic tracking and vision-based tracking, are developed [18]. Thanks to these technologies, it is possible to create a virtual hand that is driven by a data glove and a tracker. Thus, human-computer interaction becomes more natural and intuitive than the ones that use classic input devices.

2.4 Human Computer Interaction

Recently, HCI has regained popularity due to the intuitive and successful interaction techniques of devices such as tablet PCs, smart phones and even smart houses. All these applications use voice commands, mimics, and gestures to interact with humans.

Human-computer interaction with hand gestures plays a significant role in these modalities because humans often rely on their hands in communication or to interact with their environment. Therefore, hand-gesture-based methods stand out from other approaches by providing a natural way of interaction and communication [19]. Many studies evaluate gesture-based interaction techniques [20], their drawbacks [21], and propose ways to increase their effectiveness [22, 23].

2.5 Gesture Recognition

There exist various definitions of hand gestures in the literature. Some studies define gestures as only static postures [24], while others consider hand motions and trajectory information as a part of the gestures [25]. For simplicity, we consider only the hand's motion trajectory (excluding finger bending and orientation information) to define gestures in the scope of this study.

Recognizing gestures is a comprehensive task combining various aspects of computer science, such as motion modeling, motion analysis, pattern recognition and machine learning [26]. Since the beginning of the 1990s, many hand gesture recognition solutions have been proposed. These studies can be divided into two categories, based on their motion capture mechanism: *vision-based* or *glove-based*. Vision-based solutions rely on image processing algorithms to extract motion trajectory and posture information. Therefore, their success highly depends on the used image analysis approaches, which are sensitive to the environmental factors, such as illumination changes, and may lose fine details due to hand and finger occlusion.

Glove-based solutions generally provide more reliable motion data and eliminate the need for middle-tier software to capture hand positions and postures [27]. On the other hand, they require the user to wear cumbersome data gloves and position trackers, and usually carry a few connection cables. These factors reduce intuitiveness and usefulness of these methods and add extra financial cost [27].

Studies in this field can also be classified by examining whether they recognize static or dynamic gestures. Although static gesture recognition is relatively simpler, it still requires much effort due to the complexity of gesture recognition in general. Most static gesture recognition research focuses on neural-network-centered solutions [28, 29], but for dynamic gesture recognition, hidden Markov model (HMM)-based solutions are generally preferred because they yield better results [30, 31, 32]. Similar to our work, finite state machine (FSM)-based solutions [33, 34, 35] are also used to recognize dynamic gestures. Other studies suggest using fuzzy logic [36] and Kalman filtering [37] for gesture recognition.

Neural-network and HMM-based solutions for gesture recognition require extensive training data to successfully recognize gestures. Our approach, however, can achieve similar recognition rates without a large training set. The other unique advantage that we utilize from the FSM-based recognizer is that they can spot gestures in a stream of hand motion, unlike the other methods [38] where the start and end points of the gesture should be given explicitly.

Chapter 3

Motion Capture

3.1 Overview

We use our hands to perform various daily tasks, to interact with and manipulate our environment. Because they play a crucial role in our daily lives, researches have been trying to develop technologies which capture the hand movements and convey them to the computers. For this purpose, sensorized gloves started to be developed in late 1970s [39]. Sensorized gloves, also known as data gloves, may vary according to the used sensor technology, sensor number and precision. The basic idea that lies behind data gloves is to collect the joint angle values of hand fingers and transmit them to a computer via different means such as bluetooth or cable. For a more detailed survey on data gloves, you can refer to this study [39].

3.2 Data Glove

The selected data glove is 5DT Data Glove 14 Ultra [40] with USB interface (see in Figure 3.1) which collects 14 bending sensor (2 sensors for each finger and 4 sensors in abduction points) data in real time. This data glove uses a fiber optic based sensor technology. One end of fiber optic loop is connected to a LED and the other end of the loop has a photo-transistor which measures the intensity of the light returning from the other end. Since light intensity degenerated when fingers bend, the glove measures the bending values indirectly according to the light density. 5DT data glove provides data with the sampling rate which is above 75 Hz. Although there are other sophisticated data gloves exist in the market, 5DT Data Glove 14 Ultra is chosen because of its affordability and accessibility.

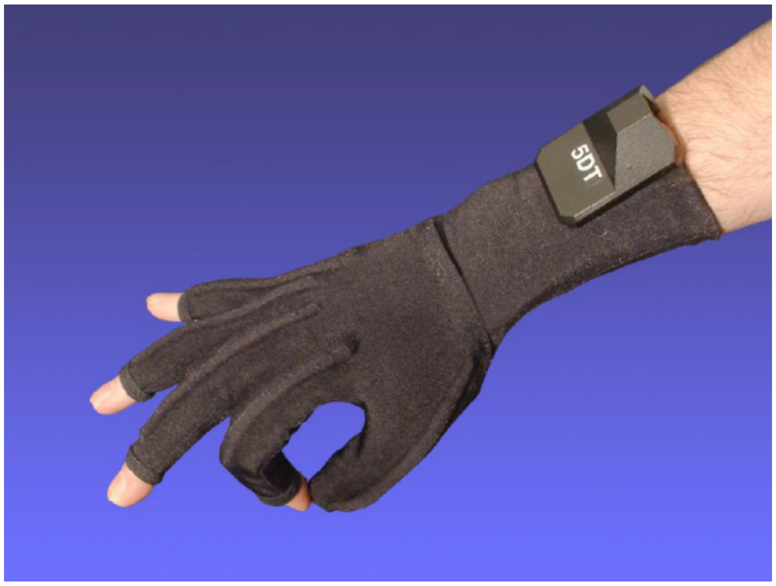


Figure 3.1: 5DT Data Glove Ultra 14.

3.3 6DoF Tracker

To be able to completely describe hand motion, knowledge of both hand configuration (amount of joint bending) and hand position in space are needed. Because the selected data glove does not have sensors for capturing the position and orientation information (total of 6 Degrees of Freedom (DoF): 3 for translations and 3 for rotations), we need to conjunct the data glove with extra accessories called 3D trackers. There are several types of 3D trackers offered over the years which diverge among each other according to their key performance parameters (accuracy, jitter, drift, latency, and so on) and technological infrastructure (magnetic, ultrasonic, optical and mechanic) [39].

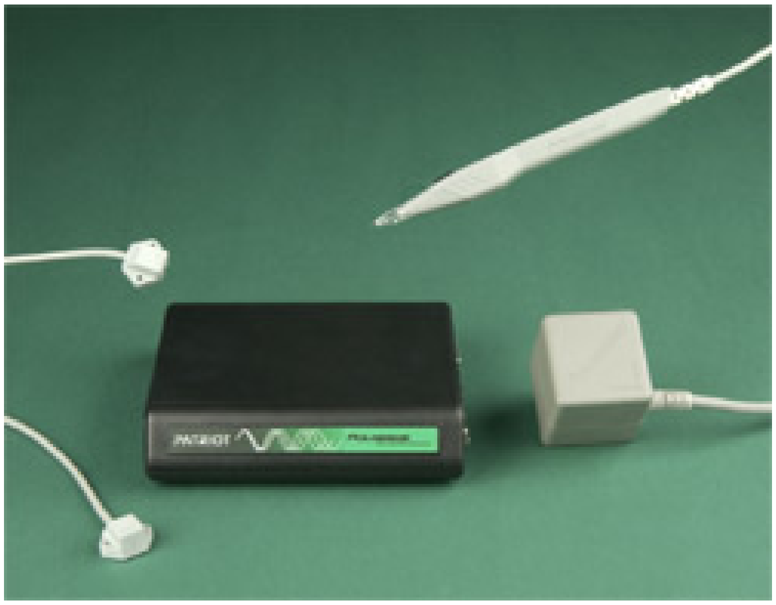


Figure 3.2: Polhemus Patriot ^{TM}.

We selected Patriot ^{TM} trackers produced by Polhemus (see Figure 3.2). It is one of the cost-effective solutions that can offer 6 DoF motion tracking with reasonable well resolution and range. It is pioneered with A/C magnetic motion tracking technology. The tracking system composed of source, sensors and a processing/transmitting unit. The source and sensor contain electromagnetic coils enclosed in plastic shells. The source emits magnetic fields, which are detected by the sensor. Orientation and position calculations are made according to the readings on the passive sensors. Some of the important company specifications of the utilized tracker are listed in Table 3.1.

Although accuracy claim is very high in the specifications, it has been experimented that when the distance between source and sensors is above 80-100 cm, the precision degenerates rapidly and causes shakes on the virtual hand driven by the tracker. Because we focus on preliminary design and accuracy range is enough as a design space for users, the problem is not disconcerting.

Degrees-of-Freedom	6 DoF
Number of Sensors	1-2
Update Rate	60 Hz per sensor
Static Accuracy Position	0.06 in RMS
Static Accuracy Orientation	0.40° RMS
Latency	Less than 18.5 ms
Resolution Position at 12 in range	0.00046 in 0.00117 cm
Resolution Orientation at 12 in range	0.00381°
Range from Standard TX2 Source	Up to 1.52 meters
Extended Range Source	n/a
Interface	RS-232 or USB (both included)

Table 3.1: Polhemus Patriot TM specifications.

3.4 Hand Model and Its Skeletal Structure

In this study, a 3D hand model that consists of a hand skeleton rigged by the hand mesh is used to render the virtual hand in the virtual environment. The hand model is designed in Autodesk 3ds Max TM Design 2011 tool. For the outer mesh, we have used a 3ds Max model of human right hand. The rough hand mesh is smoothed with “Mesh Smooth” modifier (NURBS-based subdivision method) provided by the modeling tool. Because we need to animate the virtual hand, we have created a skeletal structure inside the hand model and utilized the bone skinning modifier to attach vertices to the skeleton. The bones are deployed into the 3D mesh model with a similar structure of real human hand bone structure. The bones and joints of the hands are specifically adjusted for the data glove (see in Figure 3.3).

The vertices on the mesh model are mapped using the skin modifier of the design tool. The skin modifier provides weighted envelopes for each bone in the model. Weighted envelopes define how much the bone movement affects the vertex manipulation. By encapsulating the vertices with weighted envelopes, the effect of the selected bone is applied to the enveloped vertices (see in Figure 3.4). This procedure is repeated for every bone to cover all vertices of the model.

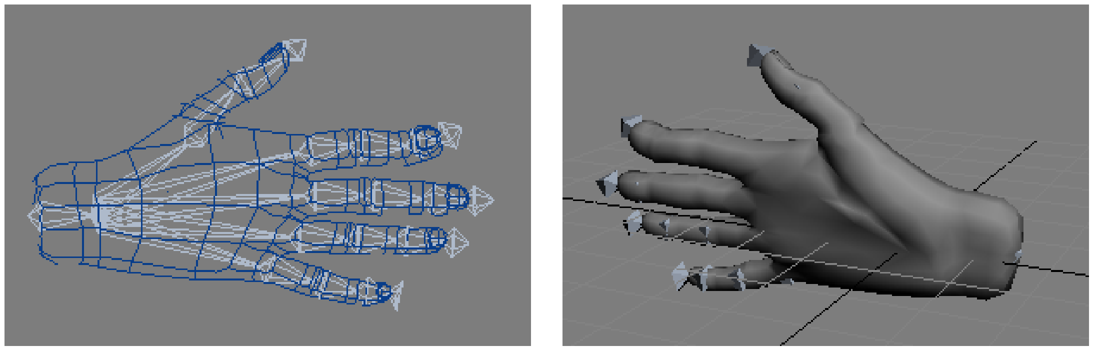

(a) (b)

Figure 3.3: Hand model: (a) skeletal structure in the model, (b) smoothed hand model.

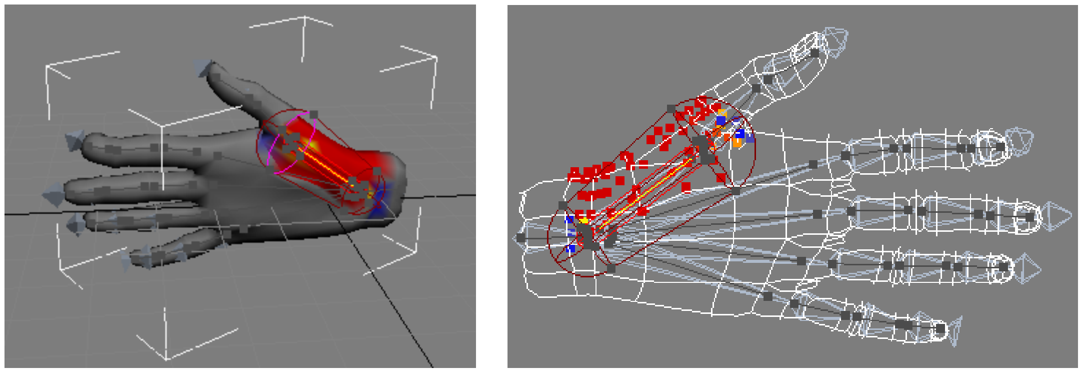

(a) (b)

Figure 3.4: Bone skinning: (a) vertices encapsulated by one of the bones, (b) weighted vertex-bone mapping.

3.5 Mapping of Inputs to the Models

Hand motion capturing using a data glove mainly has two major problems: calibration and hardware incapabilities. We try to overcome these problems by post processing the raw sensor data namely the bending sensor values. Calibration problems originate from the fact that different people may have different hand sizes and shapes which causes glove sensors to overlap on different finger locations. This seriously affects glove measurements and causes imprecisions. To reduce inaccuracies, data gloves need to be calibrated for a specific user. This procedure is done by asking users to perform gestures that generate maximum and minimum bending values on the sensors like “flat hand” and “fist” gestures for 5DT Data Glove 14 Ultra. The automated calibration mechanism applied in the data glove is based on linear polarization. After minimum and maximum readings extracted from sensors, all raw bending values are mapped between 0 and 1, respectively. The mapping function is shown in Equation 3.1.

$$output = \frac{raw_{read} - raw_{min}}{raw_{max} - raw_{min}} \tag{3.1}$$

The other problem of the glove-based motion capture is hardware incapabilities. Although human hand (see Figure 3.6) has 19 degrees of freedom excluding the wrist, the data glove can only provide 14 sensor values. In addition, sensors on the data glove do not directly correspond to the hand joints (see Figure 3.5). Thus, the contribution of the joints to the bending value on the sensors is unknown but it can be estimated using an interpolation function, which is adaptable to natural bending tendency of the fingers [27]. We use an interpolation function that defines bending values in the following manner: the start and end points define the possible minimum and maximum rotation angles respectively and specific to each joint. In this method, the additional control point is used to give an affinity value to the joint. For example, if the chosen control point is close to the minimum value, the interpolation function generates smaller angles which make the joint have the tendency of stand straight. If the selected control point is close to the maximum values, the interpolation function generates relatively greater angles even though the read bending value is small. The interpolation function is given in Equation 3.2 where α and θ denotes start and end points, respectively, and β denotes the control point. The t values in the equation are replaced by the scaled sensor value read from the data glove. The interpolated sensor values for the Equation 3.2 with different control points can be seen in Figure 3.7.

$$output = \alpha(1 - t^2) + 2\beta(1 - t)t + \theta t^2 \tag{3.2}$$

By using the natural constraints and bending tendencies of the finger joints, we can make a good approximation on the joint angles in spite of relatively

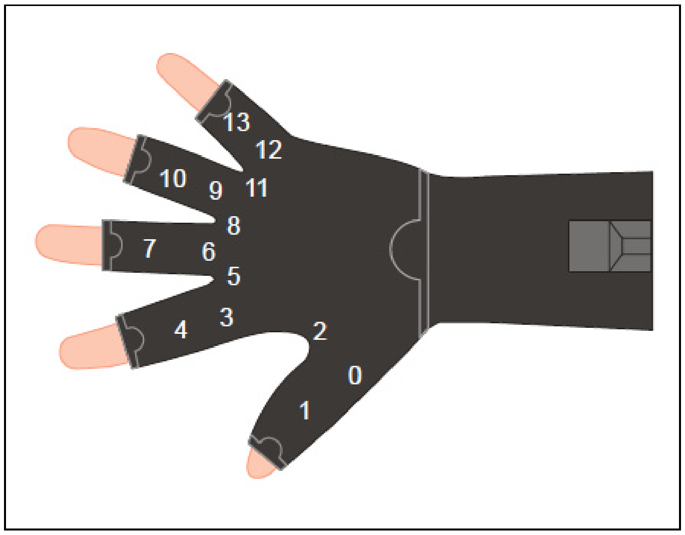


Figure 3.5: Sensors locations on the glove.

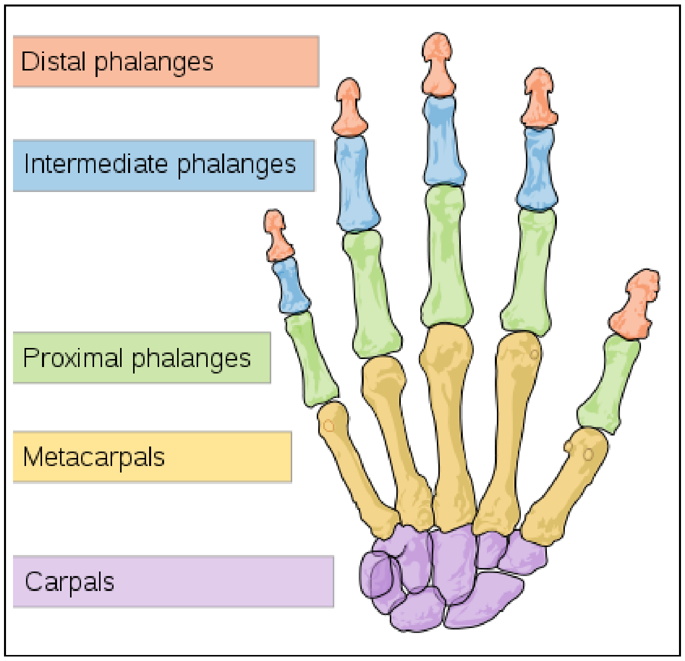
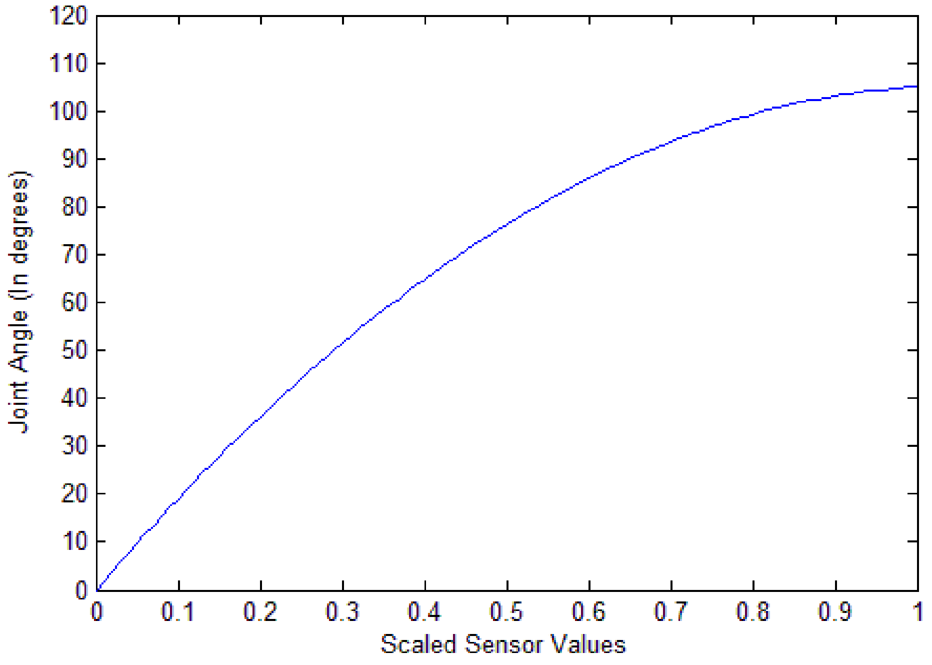
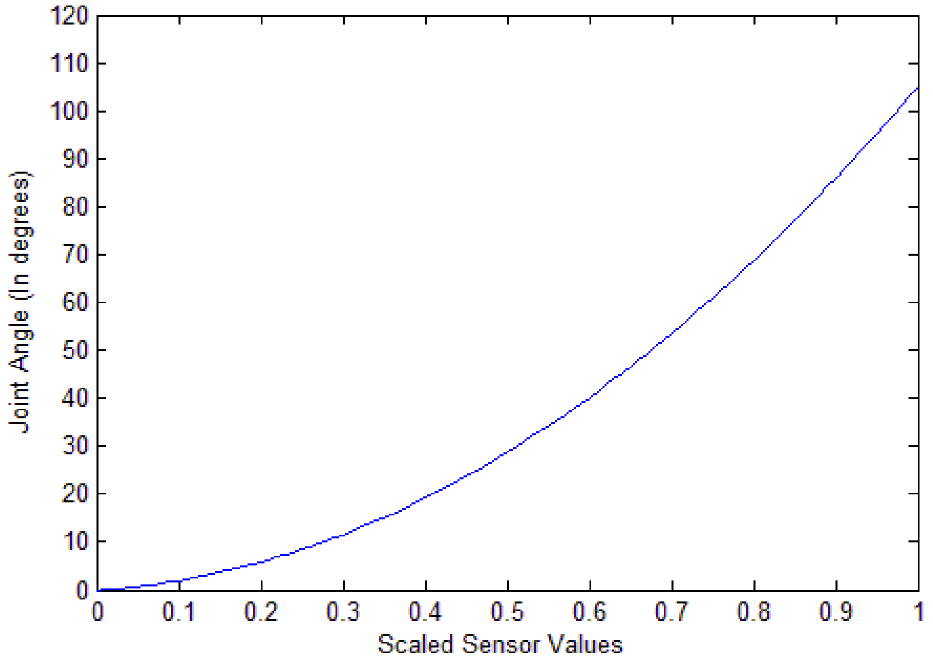


Figure 3.6: Skeletal hand anatomy.



(a)



(b)

Figure 3.7: Interpolated sensor values using Equation 3.2: (a) Control point is closer to end point, (b) Control point is closer to start point.

incorrect sensor values. Bézier curves can also be used for more controlled interpolation but single control point is sufficient in the scope of this study. The chosen interpolation values, sensor mapping and rotation constraints applied to the bones in horizontal and vertical axes are listed in Tables 3.2 and 3.3, respectively. After the proposed interpolation function produces the interpolated joint angles, orientation information are converted to quaternions for representation.

Bone	Start (°)	End (°)	Control (°)	Sensor No
little metacarpus	0	8	1	12
little knuckle	0	90	40	12
little lower	0	90	60	13
little upper	0	80	60	13
ring metacarpus	0	4	1	9
ring knuckle	0	90	60	9
ring lower	0	100	45	10
ring upper	0	90	35	10
middle metacarpus	0	4	1	6
middle knuckle	0	90	10	6
middle lower	0	105	65	7
middle upper	0	90	55	7
index metacarpus	0	4	1	3
index knuckle	0	90	70	3
index lower	0	80	30	4
index upper	0	110	65	4
thumb metacarpus	40	0	7	0
thumb knuckle	0	70	10	0
thumb upper	-5	65	15	1

Table 3.2: Interpolation values of each finger joint in the horizontal axis.

The position and orientation information captured from the tracker is directly mapped to the root bone thus every motion in the root bone is transferred to child bones. Therefore, entire hand moves and rotates at each position and orientation update.

Bone	Start (°)	End (°)	Control (°)	Sensor No
little	10	-15	0	11
ring	12	-12	0	8,11
middle	5	-5	1	5,8
index	-8	11	3	2,5
thumb	-12	20	5	2

Table 3.3: Interpolation values of each finger joint in the vertical axis.

Chapter 4

Virtual Sculpting

4.1 Volumetric Structure of Deformable Models

The proposed system represents the deformable objects (virtual clay) with a volumetric approach. The deformable objects lie on the deformation space of the virtual environment. The deformation space is a 3D grid structure where the corners of the grids contain volume elements (voxels). The selected size for the deformation space is $128 \times 128 \times 128$, which is large enough to represent detailed models and small enough to process all the space in real time with a standard personal computer (for computer specification, please see Section 1.3). The size of the deformation space can be increased to enhance the model quality and real time processing still can be achieved with more processing power.

In the proposed method, all the deformable objects consist of voxels. We place the voxels of the deformable objects on the corners of uniform 3D grid structure. A voxel is either filled or empty. A deformable object is the collection of voxel that are filled. We modify and deform the objects by toggling the state of the voxels in deformation space.

4.2 Rendering Deformable Objects

Because the used representation technique is volume based, we need to convert the model data to OpenGL ™ drawable data primitives like vertices, edges, triangles, quads. Additionally, we need to calculate normal vectors of the primitives for realistic rendering and shading. For this process, we make use of the famous marching cubes algorithm [41]. Marching cubes is an algorithm that extracts polygonal mesh of the surface from a volumetric 3D data. To be able to extract surface of the voxels in deformation space, the algorithm proceeds on each cube which consists of neighbouring eight voxels. The polygons that form the surfaces are determined according to the states of the voxels in the corners of the cube. Because there are eight corners of a cube, one of the 256 pre-calculated possible polygon configurations is selected.

To be able to utilize illumination models provided by OpenGL ™ , we need to compute the normal vector of the each vertex generated by the algorithm. Because each vertex is part of more than one polygon, we calculated the normal vector of the each vertex by interpolating normal vectors of the contributing polygons. The resulting polygon mesh from a deformable model can be seen in Figure 4.1.

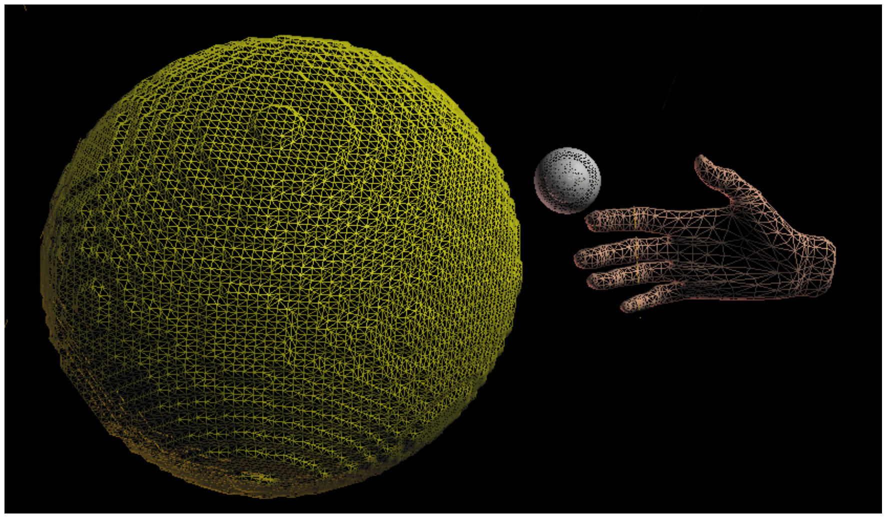


Figure 4.1: Mesh views of the deformable model, the tool and the hand.

4.3 Deformation Tools and Their Manipulations

Deformation tools in the virtual environment are the main means of deformation. They are simply 3D objects which can be used to carve material from the deformable model or stuff new material to the existing ones. Because we use point/surface-based interaction for deformation, they can be an arbitrary shape, which has a well-defined surface. (For details of the deformation techniques, please refer to Sections 4.4 and § 4.6). In the virtual sculpting application, we prefer to use 3D primitives such as cubes, sphere with various size as our deformation tools. These tools can be manipulated with the virtual hand or directly by the 6 DoF trackers.

In order to manipulate tools intuitively, we make use of grasp gesture where all of the fingers are closed like a fist. To select and move a tool in the virtual environment, users need to grasp the tool with the virtual hand firstly. For grasp action to be detected, virtual hand space and tool space should intersect and the virtual hand should perform a grasp gesture. As long as the gesture is preserved, the tool can be manipulated with the virtual hand. Manipulated (grasped) tools follow the exact same motion of the virtual hand. When the virtual hand is rotated or moved, the manipulated tool will also be rotated and moved. If the user ungrasps the virtual tool, the tool performs one of the following pre-determined action: return to its initial position or stay put in the last location of the virtual hand.

We define two different grasping methods. The first one is natural grasping in which the grasped object is transformed to a pre-determined position and orientation to fit the virtual hand more properly (see Figure 4.2(a)). The other is direct grasping in which the virtual tool is simply grasped in its current position and does not reposition itself according the virtual hand (see Figure 4.2(b)).

One of the drawbacks of using virtual hand to manipulate tools is that it requires users to perform the grasp gesture continuously during the design process. Although this act seems natural, hold action may cause fatigue for the user. Additionally, users need their hands to perform gestural commands. To

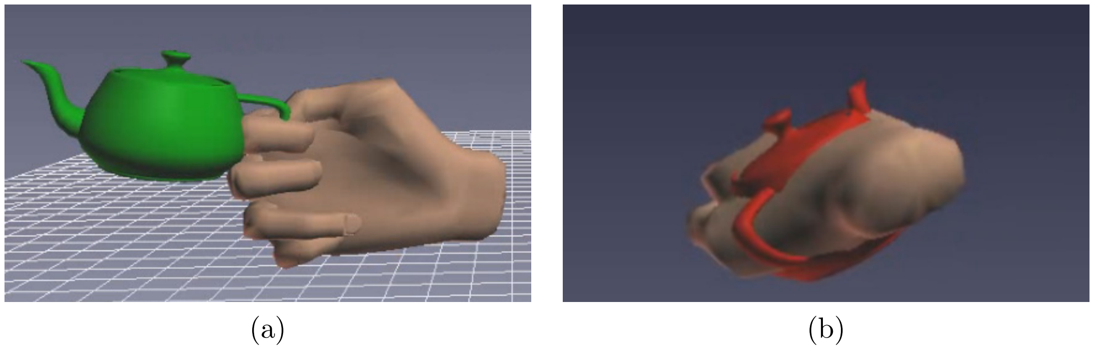


Figure 4.2: Grasping types: (a) natural grasping, (b) direct grasping.

prevent fatigue problem and free the user hand in design process, another option to manipulate the deformation tool is proposed. In this approach, the movement of the deformation tool is directly controlled by an additional position tracker. Using an additional position tracker to manipulate the deformation tools makes the deformation process more practical in term of user's endurance. To support both manipulation alternatives, we make use of the position tracker's capability of tracking two sensors at a time. One of the sensors is attached to user's hand to control virtual hand while the other sensor is bound to deformation tool to directly manipulate it.

4.4 Volumetric Deformation

Because our deformable objects consist of voxels, we design our models by two major means: carving and stuffing. Carving is an action of removing existing material (voxels) from a deformable model. The carving action is performed by simply eradicating (changing the states of the voxels into empty state) voxels that interact with the deformation tool. This creates the desired illusion of carving material which can be analogous to sculptor's carving operation on design material.

In contrast to the carving action, the stuffer supplements new material to the existing model by changing the states of the voxels from empty to filled. By doing so, it is possible to form a new model from scratch resembling adding clay to create a new design.

4.5 Collision Detection

Unlike our deformable models, deformation tools consist of triangular meshes. Thus, for collision detection, surface points on the deformation tools need to be converted to deformation space. The corresponding point in deformation space for each vertex on the surface of the deformation tool is calculated by inversing the transformations on the deformation tools. After all surfaces are transferred to the deformation space (grid), we need to check every vertex on the surface whether it coincides with one of the voxels. If the brute force approach is used, the cost of the collision detection process for each update becomes $O(M \times N^3)$ where M is the number of surface points and N is the size of one dimension. Because we have uniform 3D grid as a deformation space, it is possible to directly use the translated surface points as an index to this grid by means of floor or ceiling function. Thus, collision calculation for the entire tool can be computed in $O(M)$, which is more than enough to check collision detection in real time.

In addition to that, another collision detection method is proposed for non-uniform deformation spaces. Because the processing time is very critical for a real time design application, we reduce the search cost using an octree based search algorithm for non-uniform deformation spaces [42].With this approach, collisions can be detected in $O(M \times logN)$ for non-uniform deformation spaces.

4.6 Surface-based Deformation

Although our deformation tools do not have a volume (only have surfaces), by sweeping the deformation space with their surface points, we can stuff/carve material to/from the deformable model. Because all our deformation tools are closed, a voxel cannot get inside of a deformation tool without passing from its surface. Thus, it is not necessary to have volumetric deformation tools (models which contain vertices (voxels) inside of the tool) for deformation operations. On the contrary, volumetric deformation tools may increase the processing time because they will have a lot more vertex than a surface based shape.

On the other hand, surface based deformation tools have a major drawback. Because we only use surface points for collision detection, we may skip some voxels at the locations where surface points on the tool are sparse. To overcome this problem, we added more surface layers inside the deformation tools. If a voxel can pass through outer surface, it coincides with one of the inner surface layers and deformation action is applied to this voxel.

Because we use surface-based deformation, any model which has dense surface point distribution can be used as a deformation tool in the proposed system. To display this functionality and create a more life-like design experience, we used virtual hand directly as a deformation tool. Because it has a well-defined surface and a closed 3D shape, users can directly design the deformable models just using their hands to control virtual hand.

During the deformation phase, another normal calculation approach is used to increase the quality of the illumination on the deformable model. The inverse of the surface normal (tool surface) is applied to the deformed voxels, which enhances the perception of deformation done by the deformation tool.

4.7 Visual Force Feedback

In real life design process, touch sense helps designers to capture the shape of the model while force feedback from the designed material helps them make fine adjustments over the deformable model. Without using additional force feedback hardware, it is difficult to convey this information to the users. In order to overcome this problem, we add a visual force feedback indicator (see Figure 4.3) to the proposed system. The force feedback indicator works similar to the real life equivalent. It shows the amount of material being modified (carved or stuffed) as users design the deformable models. The intensity (force) on the indicator is calculated by counting the number of voxels being edited. When the number of edited material increases, the force bar in the indicator rises and the colour of the bar turns red from green. Although visual force feedback indicator cannot provide the life like design experience and touch, it helps user to capture the touch sense in a limited way.

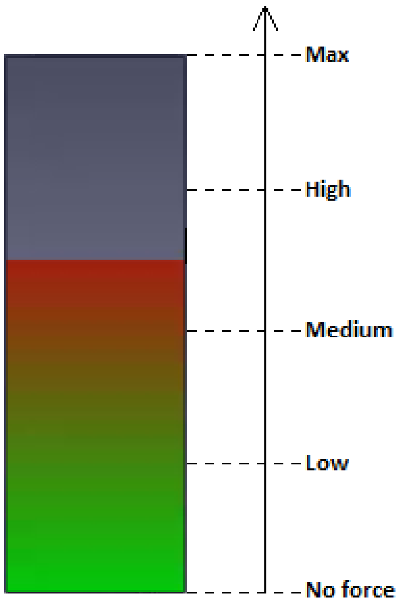


Figure 4.3: Visual force feedback indicator.

Because we use 2D displays in our application, providing depth perception for users is a very difficult task. The visual force feedback indicator also helps users to understand the depth information by evaluating the number of modifications.

Chapter 5

Human Computer Interaction

5.1 Overview

User interface design and how users interact with the user interface elements is one of the most crucial design aspects of a computer application. Because we offer natural hand based interaction to users, a user-friendly interface design that is suitable for the utilized input device is necessary. To accomplish this task, we provide two different approaches:

The first component of our gestural interface is the *hand mouse*. Because our users wear data gloves, they may not control the mouse effectively. To overcome this interaction problem, we specifically design an interaction method in which users can manage the mouse with data glove and position tracker effectively. With this method, the user can interact with classical GUI items such as windows or buttons.

The other component that we introduce is a gesture-based command interface. Users can direct and command the application by performing trajectory based hand gestures. The gesture vocabulary and their recognizer machines can be generated by supplying only few sample gesture data for each gesture. This feature allows users to create their own gesture commands for a particular task according to how they think it suits the action. Because the gesture-command interface has a general architecture, it is not limited to virtual sculpting tool. It can be used in any context to command applications or devices such as TVs or e-Readers with gestural commands.

5.2 Hand Mouse

Because the user has limited access to mouse while wearing data glove, a mouse like interaction cursor is developed which can be manipulated with the virtual hand. The GUI elements of the proposed system are very similar to classical GUI elements. In the scope of this study, simple rectangular buttons are utilized as means of interaction. The intuitive and novel part of the user interface is the cursor that manipulates these buttons. The cursor of the design application is controlled by the position tracker and the data glove unlike classical cursors that are controlled by a mouse.

During the design process, the cursor is hidden to allow access to hand-based deformation. In order to activate the cursor to interact with user interface elements, users just need to perform a specific static gesture, which is a "point gesture" where all fingers closed except the index finder. When this gesture is detected, virtual hand that is used for design process disappears and system goes into the GUI interaction mode. The GUI interaction mode stays active as long as the gesture is preserved. When GUI interaction mode is activated, a mouse cursor appears. The movement of the cursor is controlled by the position tracker. Users can move the cursor naturally by moving their hands that are attached to the position tracker. Positions of the hands are transformed to 2D coordinate system by dropping the depth information collected from the input device. In other words, cursor follows the hand motion of the user in a manner that simulates mouse motion. A "mouse click" is simulated by bending the index finger. Bending state of the index finger is like mouse button pressed action.

GUI interaction is performed in the following manner: when a user wants to interact with a GUI element, he/she basically moves the cursor over the GUI element by moving his/her hand. When the cursor is over the GUI element, user simply bends his/her index finger to click on it to perform the action that is related to respective GUI element. The proposed interaction technique removes the need for a mouse considerably and makes the GUI action more suitable for the application.

5.3 Gesture Detection and Recognition

Similar to the other gesture recognition techniques, the proposed approach consists of two stages: *learning* and *recognition*. In the learning stage, the user is asked to repeatedly perform a particular gesture. The system records the motion trajectory of each gesture sample with a magnetic 3D position tracker attached to the user's hand. Unlike the other approaches [43], motion data is collected by recording the relative position of the hand according to its previous location, instead of recording the absolute positions. Additionally, threshold-based filtering is applied to the collected data to reduce noise caused by unintended vibrations and tracker precision errors due to distance range of the sensor. Next, collected motion data is filtered using a component-based sliding window technique for smoothing and further noise removal. Then, the filtered trajectory information is transformed into our gesture representation format, which is basically an ordered sequence of events (directional movements).

In the last step of the learning phase, our method chooses a few event sequences (using the Needleman-Wunsch sequence-matching algorithm [44]) from the provided samples to form a base for gesture recognizers. The algorithm compares every pair of event sequences (gesture pairs) and computes a similarity score for them. The event sequences with the highest similarity scores are selected to form the bases for the gesture recognizers. Then, a recognizer finite state machine (FSM) is generated based on these chosen gestures. Because FSMs are sequence recognizers, each forward transition in a generated FSM corresponds to an event in the selected sequence in the respective order. This learning phase is repeated for every distinct gesture, with several FSMs produced for each.

In the recognition stage, continuous inputs from the tracker are processed in a similar manner as in the learning stage and fed to all the recognizer machines. If one of the previously captured event sequences occurs during the session, the respective recognizer machine traverses all the states and reaches the final state (the accepting state). The resulting gesture recognition event triggers the action assigned for the gesture. With this approach, gestures can be recognized in real time.

5.3.1 Gesture Representation

In gesture recognition, representing gestures is a critical issue. We define gestures as a series of events performed consecutively. For trajectory-based dynamic gestures, this is a valid definition because trajectories are a series of directional vectors combined in a particular time interval. In our case, events are directional movements and a gesture is an ordered sequence of these directional movements (see Figure 5.1).

In this study, we limit the trajectories to the xy-plane for simplicity. Our representation not only allows creating many interesting gestures, it also improves the robustness of the algorithm. It is possible to extend the event (gesture) alphabet with the third dimension, or with other features such as finger movements. Using only 2D, there are eight different directional movements: $(+x)$, $(-x)$, $(+y)$, $(-y)$, $(+x, +y)$, $(+x,\ -y)$, $(-x,\ +y)$ and $(-x,\ -y)$, and they constitute a gesture space large enough to represent a variety of gestures.

To capture hand motions, we use the same six-degrees-of-freedom (DoF) magnetic motion tracking device. The device has a 60 Hz update rate for each sensor, but in our experiments, we observe that a 20 Hz rate is sufficient to teach and recognize gestures. Although we use hardware-based tracking, it is possible to employ computer-vision-based tracking for a more intuitive solution. Because the required motion capture technique does not need a fast update rate or high

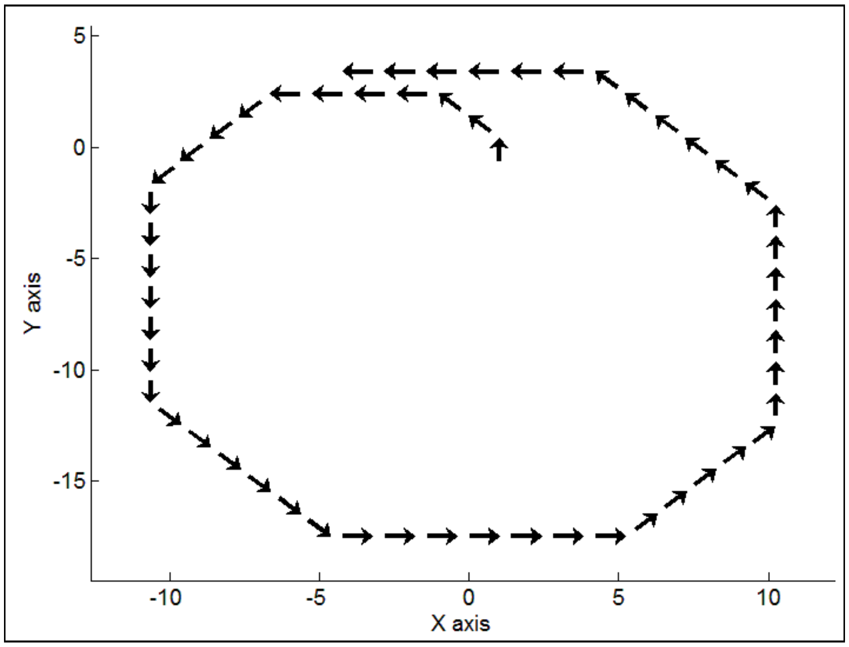


Figure 5.1: A gesture (circle) is represented as an ordered sequence of directional movements.

accuracy, it is also well suited for camera tracking. The cheaper motion tracking devices utilized by Nintendo Wii ™ or Microsoft Kinect ™ can also be used as the motion capture medium for the proposed approach. Gestures are represented as small directional movements so there is no need to maintain the absolute position. This advantage therefore makes the offered solution naturally applicable to accelerometer based motion tracking algorithms. Collected motion data in absolute position format is converted to relative position data (gradient form) while recording. In other words, when the tracker sends a new position reading, its position relative to the previous reading is noted and the direction of the movement is calculated. However, to prevent noise that may be caused by small vibrations in the hand and/or by tracker inaccuracies, relatively small changes from the previous recording are not recorded (see parameters 1 and 2 in Table 5.1).

5.3.2 Smoothing and Selection of Best Gestures

Although filtering is applied during the motion capture phase, the collected trajectory data may still contain events that are not part of the gesture due to user reaction error during the initial and final moments of the recording. There also exist a few events that do not fit the natural flow of the trajectory especially at points where a major direction change occurs (see Figures 5.2 (a) and (b)). To eliminate these minor errors, the beginnings and endings of the trajectory records are discarded (see parameter 3 in Table 5.1) and a smoothing process is applied to the collected motion data. We use a simple sliding window filter for smoothing. The windows run on the collected data for majority-based filtering (see parameter 4 in Table 5.1). An input gesture motion data and the results of the applied filtering are shown in Figure 5.2.

In the ideal case, when the same gesture is performed, it would yield the same event sequence so the recognizer could be formed from just one gesture sample. However, due to the nature of trajectory-based gestures and filtering errors, the captured gesture samples may not be identical in terms of the resulting event sequences (Figure 5.3). To determine the correct series of events that a gesture contains, the system needs several samples of trajectory information, from which "the best" event sequences are chosen. These choices are made by the Needleman-Wunsch [44] sequence matching algorithm that produces a similarity score, which is a global sequence alignment algorithm commonly used in bioinformatics to align two protein or nucleotide sequences. The alignment procedure also computes a similarity score between two sequences. Similarity scores are calculated according to a similarity matrix/function for the characters in alphabets (events). Because events are vectors in our case, the similarity of two "characters" is calculated using the distances between vectors. The gap penalty for the sequence matching algorithm is set to a value higher than the maximum distance between the vectors to achieve the same length gesture sequences (see parameter 5 in Table 5.1)

A total similarity value for each sequence is acquired by summing its pair-wise similarity scores. Then, the highest n (see parameter 6 in Table 5.1) event sequences are selected to later create recognizers. In other words, gestures that are located closer to the center of the gesture cluster are selected because they are more likely to generate a more generic sequence of events, which can then be used to form the bases for gesture recognizers.

5.3.3 Generating Recognizers

Because strings and our gestures are represented in the form of event sequences, an analogy between string and gesture recognition problems can be made. When we convert the gesture sequence in Figure 5.2 (c) into a string, we see the following expression:

$$\begin{aligned}&(+x)\,(+x)\,(+x)\ \ldots\\&(-x,\ -y)\,(-x,\ -y)\,(-x,\ -y)\ \ldots\\&(+x)\,(+x)\,(+x)\ \ldots,\end{aligned}$$

which can be expressed with the following regular expression:

$$(+x)^+\ \ (-x,\ -y)^+\ \ (+x)^+\ .$$

Because our gestures can be represented as regular expressions, an FSM-based recognizer becomes a natural and suitable solution among alternatives. To establish the recognizer machine, we use the gestures (sequences) that were selected in the previous step (see Figure 5.4 for a sample gesture recognition machine for the gesture in Figure 5.2 (c)).

Using FSMs as recognizers ensures that the resulting machines are scale invariant, which means that if trajectories are repeated on a higher or lower scale it can still be recognized. As long as the order of events is preserved, the number of repetitive events does not affect the recognition result.

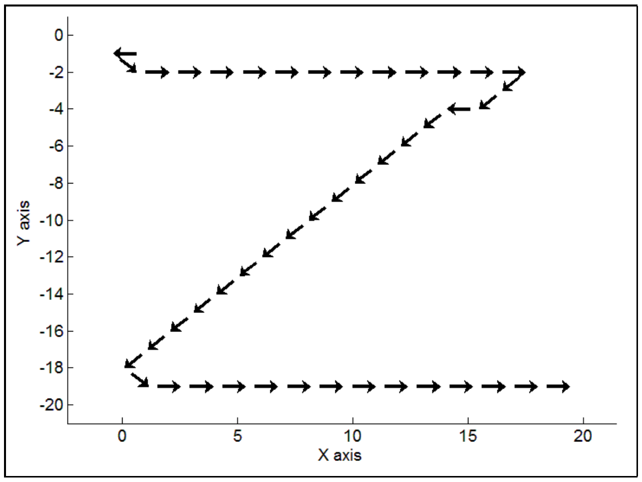
During the learning phase, a total of $n \times m$ recognizer machines are generated separately, where m is the number of gestures and n (see parameter 6 in Table 5.1) is the number of selections in the previous stage.

5.3.4 Online Gesture Recognition

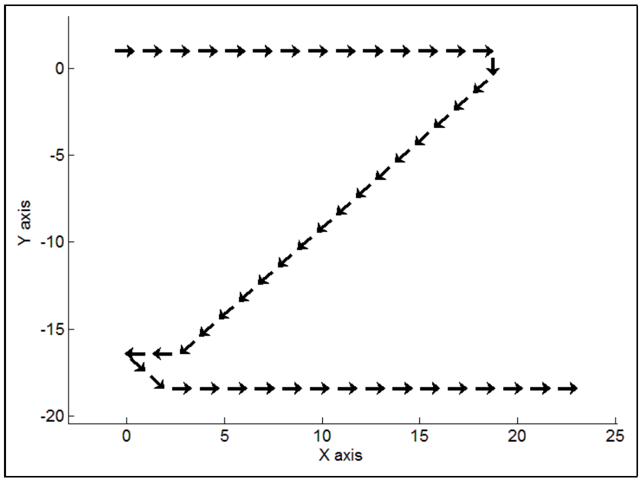
Online recognition of dynamic gestures is achieved using the previously generated sequence recognizers. When the position tracker attached to the user's hand is activated, it starts to continuously transmit position information to the system. The received absolute position data is converted to the relative (gradient) form and filtered as in the learning phase to reduce the effects of small trajectory errors and to improve the robustness of the algorithm.

Before the filtered event data is fed to all recognizer machines in a continuous manner, online filtering is applied to the newly received data to determine whether it is consistent with the previous events. Inconsistent events are not sent to recognizers because they are not part of the intended gestures. The received events cause state transitions in the recognizer machines. When a machine reaches its accepting state, a gesture recognition event is triggered immediately.

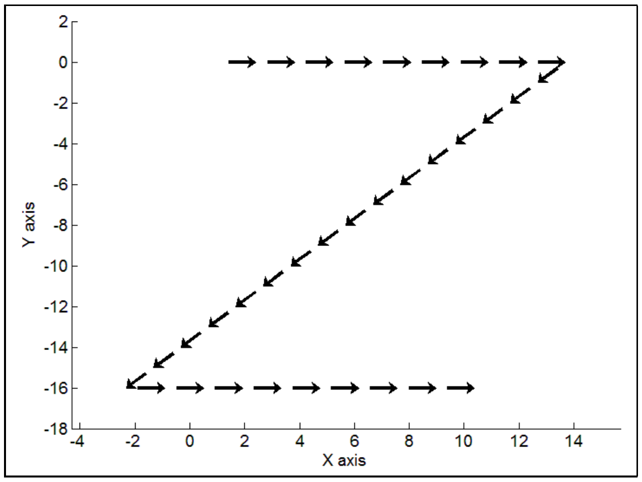
If no state transitions are detected for a particular time interval, a time-out (see parameter 7 in Table 5.1) mechanism is triggered and the gesture recognizer is reset to the initial state to prevent unnaturally long waits for a gesture recognition event. In the proposed approach, there is no need to specify a gesture's start and end points because the machine returns to its initial state automatically in the event of an incorrect gesture input or a time-out.



(a)



(b)



(c)

Figure 5.2: Two raw gesture motion data (a and b), and the result of the applied filtering (c).

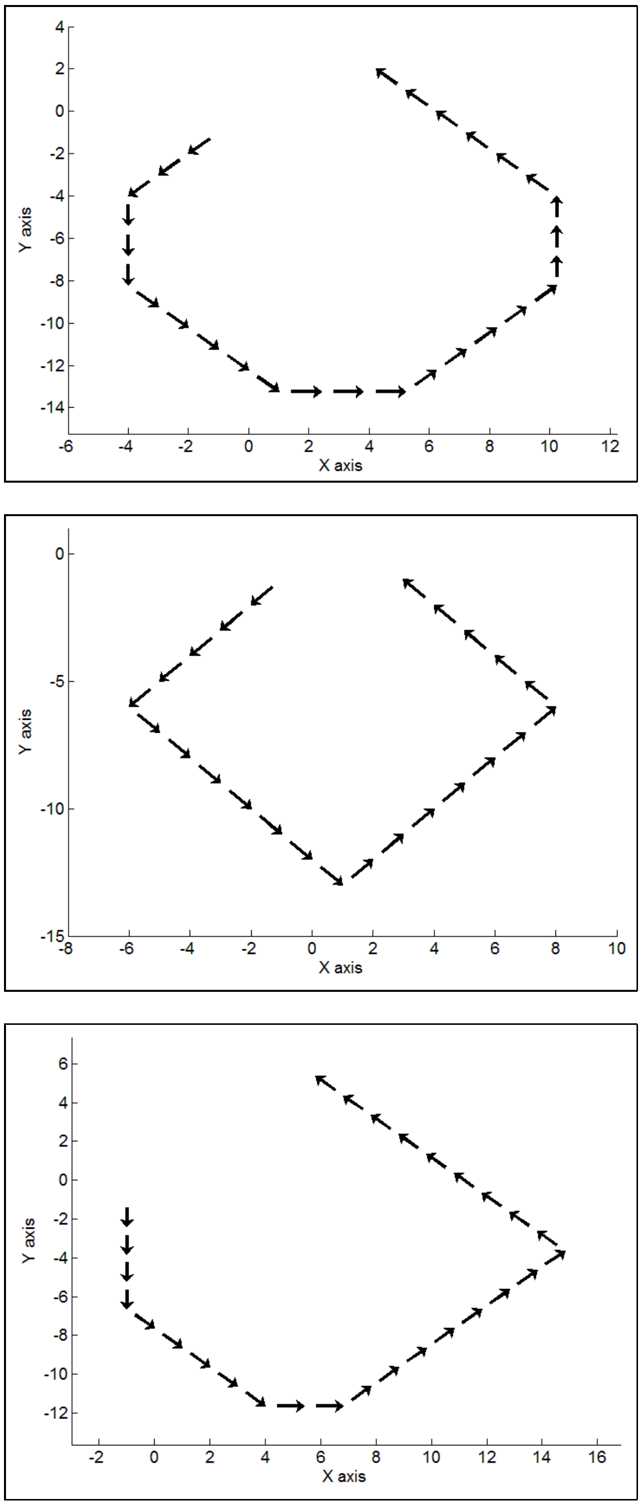


Figure 5.3: Captured gesture samples may be different due to the nature of trajectory-based gestures and filtering errors.

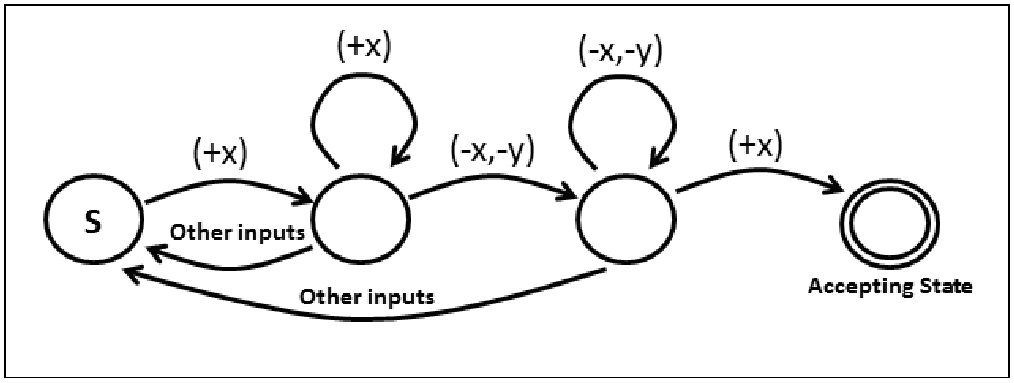


Figure 5.4: A sample gesture recognition machine to recognize the gesture in Figure 5.2 (c).

No	Parameter	Value	Description
1	Motion capture threshold	3 cm	If the displacement in hand position is lower than the motion capture threshold, it is ignored for the learning and recognition stages.
2	Component angle threshold	25°	If the angle between the motion vector and its x, y components is less than the component angle threshold, the respective component of the movement is ignored for the learning and recognition stages.
3	Skipped inputs	5	The number of skipped inputs at the start and end of the motion capture.
4	Smoothing window size	11	The previous and subsequent five records are considered with the processed input, and the majority of these records are assigned to the processed input.
5	Gap penalty	3	The gap penalty value for the Needleman-Wunsch algorithm.
6	Selection count	3	The number of best sequences selected from the recorded trajectory motion data.
7	Recognition time-out	1500 ms	If no state change is detected in a gesture recognizer by the end of the time-out period, the state machine is reset to the initial state.
8	Gesture sample count	8	The number of trajectory motions recorded for the learning stage.

Table 5.1: The parameters used for the gesture recognition experiments.

Chapter 6

Results and Discussion

6.1 Experiment

We conducted a user study in order to assess the usability of the proposed virtual sculpting and gesture recognition technique. We selected a pre-trained gesture vocabulary that consists of eleven gestures (see Figure 6.1) to evaluate the presented gestural command interface. Each gesture in the vocabulary is mapped to a specific task/action that can be performed in the application (see Table 6.1). Although we limit the recognizable gesture space with eleven gestures, the gesture vocabulary can be easily extended by the fast learning method described in the previous chapter. The parameters used in the learning stage to establish the recognizers for the gesture recognition library are given in Table 5.1.

We assess the technique in terms of performance and attitude criteria [45]. The performance criterion is the gesture recognition rate. To measure the recognition rate, we carefully observe each participant individually and count the number of trials for a gesture to be recognized. In case of attitude evaluation, we used the following seven criteria: *usefulness*, *learning*, *memory*, *naturalness*, *comfort*, *satisfaction* and *enjoyment*. A questionnaire containing these criteria were filled by the participants using a Likert scale from 1 (strongly disagree) to 5 (strongly agree) to assess the proposed HCI approach.

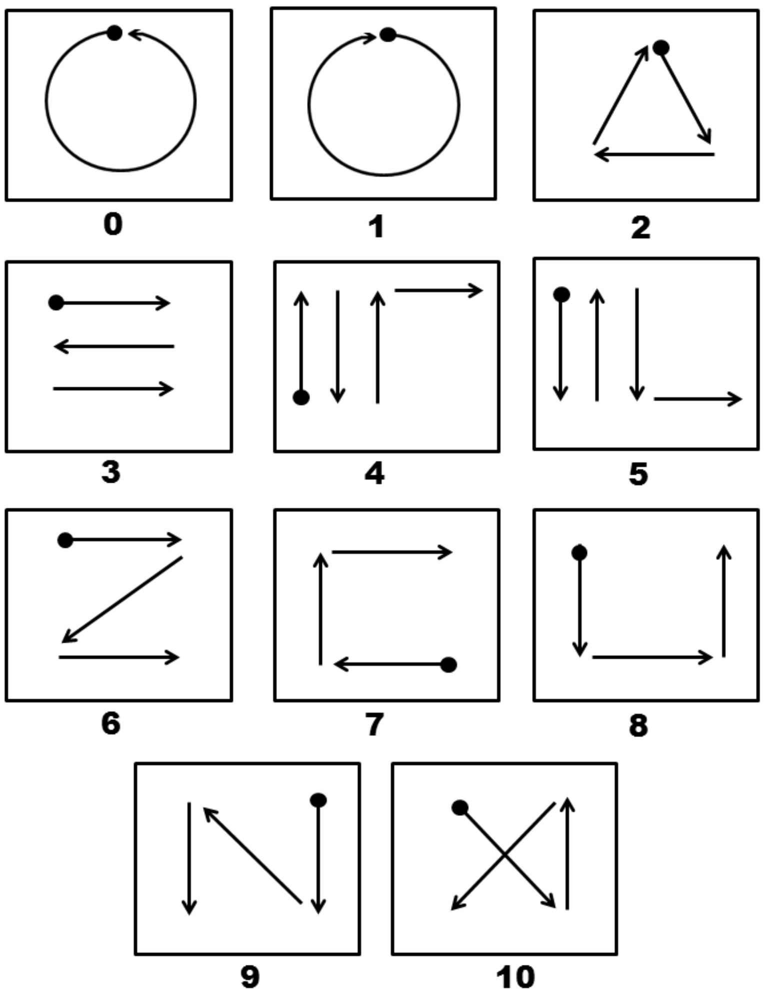


Figure 6.1: Gesture vocabulary used in the experiments.

Gesture No	Action
0	Rotate the model counter-clockwise
1	Rotate the model clockwise
2	Activate/deactivate tool
3	Change tool mode (Stuffer/Carver)
4	Increase tool size
5	Decrease tool size
6	Activate/deactivate hand deformation
7	Save the model
8	Load the model
9	Activate/deactivate hand mouse
10	Exit the program

Table 6.1: Gesture-action mapping.

A total of 30 volunteers with the average age of 28 (5 female, 25 male) were recruited to participate in the study. The participant's occupation varied; the group included computer scientists, engineers, accountants and economists. None of the participants reported previous experience with virtual sculpting tools, gestural interfaces or similar but, all of them were familiar with the classical input devices because they use desktop computers on a daily basis. The experimental set-up consists of a standard laptop computer (1.3), 5DT Data Glove 14 Ultra with USB interface and Patriot^{TM} tracker (Polhemus^{TM}) with two tracking sensors.

Each participant was trained on the aim of the virtual sculpting application and how to perform the gestures to command the application before the experiment. Then, the participants of the user study were asked to design simple models that requires the usage of these actions that are mapped to dynamic hand gestures so that the participants experienced and evaluated the new technique while designing basic models. The experiments approximately took 20-25 minutes (including the training phase) for each participant.

The performance results that present gesture recognition rates are displayed in Table 6.2. The mean and std statistics of the survey on the seven attitude criteria are listed in Table 6.3.

Gesture No	Number of Gesture Trials	Number of Successful Recognitions	Recognition Rate
0	321	223	0.69
1	306	198	0.67
2	220	135	0.61
3	112	101	0.90
4	238	193	0.81
5	249	204	0.82
6	106	75	0.71
7	89	69	0.78
8	101	84	0.83
9	218	137	0.63
10	38	34	0.89
Total	1998	1453	0.73

Table 6.2: Gesture recognition rates.

Criteria	Average	Standard Deviation
Usefulness	4.24	0.62
Learning	4.38	0.61
Memory	3.90	0.76
Naturalness	3.79	1.06
Comfort	3.17	0.87
Satisfaction	4.21	0.66
Enjoyment	4.59	0.49

Table 6.3: Results of the user attitude survey.

6.2 Analysis and Discussion

6.2.1 Performance

The performance results of the experiment (See Table 6.2) show that the average recognition rate of the algorithm is approximately 73% from a stream of motion. This indicates that a standard user should perform a gesture 1 / 0,73 = 1.37 times to trigger an application functionality. Thus, we can claim that recognition rate of the proposed technique is high enough to be used as a reliable human-computer interface. Because of the differences in the gesture definitions and the gesture vocabularies, we cannot compare our method with other methods in terms of gesture recognition performance.

The experiments also show us that sensor incapability of the magnetic tracker is one of the main reasons behind the unrecognised gestures. When the distance between the sensor and the magnetic source exceed certain point, the accuracy of the tracker drops dramatically so after this point, the tracker cannot detect the position of the hand accurately enough to correctly form the gesture sequence. This problem can be eliminated by using a more powerful position tracker or an alternative position detection approach, such as image processing or inertial motion capture techniques.

We also observe from our experiments that most of the unrecognised gestures occur in the initial learning phase due to the ill-formed gestures. After the users are adopted to the new interface, the performed gestures become healthier (more detectable) and recognition rates increase dramatically. This indicates that higher recognition rates that reach up to 90-95% can be expected from an experienced user.

6.2.2 Attitude

The outcome of the attitude criteria denotes that the participants of the user study find the proposed human computer interface and the virtual sculpting tool *useful* (4.24) and *satisfactory* (4.21) with very high attitude scores. This is promising for the proposed technique, because it indicates that the presented gestural interface can be an alternative interaction approach for classic HCI interfaces.

A surprising result of the attitude evaluation is the relatively low *naturalness* score (3.79) with respect to the other criteria, because our claim is to achieve more natural and intuitive HCI interface. However, the critical information for this attitude criterion is the high standard deviation factor. While some participants think that the pre-selected gestures are very natural for the assigned actions, the others find them quite unnatural. This shows that naturalness is fairly relative to the user. Because the proposed approach is highly adaptable with the fast learning algorithm, the user can replace the assigned actions and gestures with more suitable and natural ones for themselves. This makes the presented technique more superior than the other gesture recognition algorithms that are not easily adaptable such as HMM-based approaches, which are hard to train.

The lowest attitude criterion is *comfort* (3.17) because of the following two reasons: the users have to perform gestures repeatedly which can be exhausting after some time and they have to wear cumbersome motion capture hardware which is not comfortable. The cumbersome equipment problem can be solved by using an alternative motion capture approach that does not require users to wear gloves or attach motion tracking devices. The fatigue problem is relatively insignificant for applications that do not necessitate continuous interaction. However, it might be a good idea to establish a hand supporting/resting instrument for applications that need constant interaction for a long time.

The *learning* is one of the strongest aspects of the application. As it is explained in the performance section, the gesture recognition rates increase noticeably after a few trials. This indicates that users can learn and adapt to our virtual sculpting application in a very short time. This consequence is also supported by the high *learning* (4.38) score in the user's attitude survey. Interestingly, the highest attitude score of the tool is *enjoyment* (4.59). This result evidence that when more natural and intuitive interaction approaches are utilized, the demanding and tiresome design process become quite enjoyable. Our virtual sculpting tool makes the whole design process more fun. This also contributes the creativity and productivity of the design artists. [45]

As a consequence, sufficiently high recognition rates prove the effectiveness of the presented approach to recognize simple and natural gestures that are suitable to command applications. The assessment of the attitude criteria points out that proposed HCI technique can be utilized as an intuitive and natural interface.

6.2.3 Learning Parameters

We also emphasize that the selected method parameters have a critical effect on recognition rate. We observe that small values for *motion capture* and *component angle threshold* (see parameters 1 and 2 in Table 5.1) decreases the recognition rate dramatically because the system records small changes in trajectory that are not part of the intended gesture. On the other hand, choosing a large value for these parameters causes to miss some events that are a part of the intended gesture.

Smoothing parameter (see parameter 3 in Table 5.1) also has an important effect on the accuracy, similar to threshold parameters. A large window size causes fine details of the motion to disappear, while a smaller window size may not be able to achieve sufficient smoothing to form gesture recognizers.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

We have offered a simple virtual sculpting tool that can be utilised to design preliminary/conceptual models in a more natural and intuitive way thanks to the proposed gestural human-computer interaction approaches. The tool tries to simulate the real world clay potter scenario in which the skilled artists shape models by stuffing and carving materials in/out into/from clay either using some design tools or their bare hands.

The proposed HCI approach makes use of the advanced motion capture hardware namely data gloves (5DT Data Glove 14 Ultra) and 6 DoF magnetic motion trackers (Polhemus Patriot ^{TM}). System users wear the data glove with attached tracker to control the virtual hand placed in the virtual design environment. Virtual hand is a 3D mesh model whose vertices are mapped to a internal hand skeleton. The user's finger movements captured by the data glove, firstly, processed with a parametrized interpolation function to reduce the effects of the data glove limitations. Then, the captured bending data are mapped to the mesh model thanks to the model's internal skeleton. The orientation and position of the user's hand are collected by the tracker and directly mapped to the hand's root bone to fully simulate the real hand motion.

The virtual design environment also contains a deformable model and a few deformation tools. The deformable model has a volumetric structure and is a collection of filled volume elements (voxel). The deformable model is positioned on a uniform 3D grid where the voxels lie on the corners of the gird. We deform the model by toggling the state of the voxels between filled and empty. The volumetric model is rendered by the marching cubes algorithm.

On the other hand, the tools in the virtual design environment are basic mesh models. The virtual hand manipulates these tools by grasping and relocating them in the virtual environment. Manipulation of the tools can also be achieved by directly attaching to a 6 DoF tracker. The interactions between the deformable model and the design tool are accomplished by a real time collision detection algorithm. The collision of the tool and model is calculated for only the surface points on the tool. To overcome the sparse surface points problem, a layered surface definition is utilized. Because our hand model has a mesh structure, the user can also deform the model directly with the virtual hand thanks to the surface based collision detection algorithm.

The other contribution of the study is the innovative HCI approach. The interface has two major elements: hand mouse and gestural command interface. Hand mouse is an alternative mouse like interaction approach in which users use their hands instead of a computer mouse. The movements of the cursor are controlled by the hand motion and system users can click the conventional GUI elements by slight finger movements.

The other component is the gestural command interface. The proposed approach is a simple yet powerful technique to detect and recognize trajectory-based dynamic hand gestures from a stream of motion in real time. Gestures are represented with an ordered sequence of directional movements in 2D space. Gesture motion data is collected by a magnetic position tracker attached to a user's hand, but the proposed method is also applicable to motion data gathered using computer-vision-based approaches, inertial motion capture algorithms or popular gaming interfaces used by Wii^{TM} or Kinect^{TM}. Motion data in absolute position format is converted to our representation form during the motion capture phase.

We introduce a fast learning methodology to facilitate adding new gestures to the recognizable gesture set. A few sample gestures are sufficient to form the gesture recognizers. The learning samples are smoothed to eliminate errors generated by the imperfect nature of human capture data. From these filtered samples, the best sequence of events (directional movements) is selected using the Needleman-Wunsch sequence matching algorithm. The selected learning samples are later processed to generate the gesture recognizers, which are basically FSM sequence recognizers.

The experimental results show that the proposed algorithm can recognize dynamic hand gestures with an average of 73% accuracy in real time for a vocabulary of eleven gestures from continuous hand motion. The proposed technique's high accuracy rate and online recognition mechanism make it easily adaptable to any application for gesture-based HCI. As a result, those applications will become more intuitive in how they interact with their users.

Another contribution of our approach is that a user can create a gesture command set specific to him or her without the need for extensive training, unlike neural-network and HMM approaches. In this way, the HCI process becomes more natural and intuitive. The other favourable functionality that other dynamic gesture recognition approaches do not provide is that it can also detect and recognize trajectory based dynamic hand gestures without specifying gesture start and end points thanks to FSM recognizers. This advantage also improves the intuitiveness of the procedure.

User's attitude evaluation survey denotes that the presented virtual sculpting tool is a *useful* and *satisfactory* alternative to the classical CAD applications. The projected gestural interface provides natural and intuitive interaction mechanism, which makes the tool more *natural* and *enjoyable*. Although the gestural interface is not very *comfortable* for long time use, it is applicable to many other tools and application. In conclusion, the proposed virtual sculpting tool with the advanced gestural interface is very promising and shows great potential.

7.2 Future Work

Virtual reality and HCI are ever growing fields with the contribution of many researches. Because of these new developments and advances in technology, the future improvements to existing approaches become countless. There are a few subjects that we plan to extend and improve our work. The first and the most important of them is force feedback. Many artists and designers rely on the tactile feedback during the design stages. The clay artist/designers stress out this fact in our discussion when we exchange thoughts about the virtual sculpting approaches. Because the touch feeling is very crucial, the virtual sculpting solution without the tactile feedback seems to lack one of the very important components. However, the answer to this problem is neither easy nor cheap. There are a few tactile feedback devices available. Our volume-based deformation approach is very suitable to be used with these devices. The visual force feedback indicator can be replaced with an effective force feedback solution which can greatly enhance the intuitiveness of the tool.

The other contribution of the tactile feedback would be to the tool interaction. When the user's hand follows a trajectory which causes the virtual hand passes through one of the virtual objects such as tools and models, the realism of the interaction diminishes. If this collision problem is only solved in the virtual environment, the synchronization of the real hand with the virtual hand is lost. However, if we can deploy a force feedback device that stops the real hand at such collision points, the interaction between the tool and virtual hand become more realistic.

Another improvement can be made in visual feedback side. One of the known problems of our system is depth perception. Our digital design environment is in 3D but we only use 2D displays to visualize the virtual world. The loss of the third dimension negatively affects the overall quality of the design process. By taking advantage of stereoscopic displays, the depth information can be conveyed to the user and a more realistic virtual environment can be achieved.

As a future work to gestural interface, gesture space dimensions can be extended to increase the number of recognizable gestures. For this purpose, depth information (z-coordinate) can be added as the third dimension of the gesture space. To add some constraints to recognized gestures or to recognize orientation-based gestures, palm orientation can be utilized. We also plan to combine the proposed dynamic gesture recognition approach with dynamic posture recognition by using a data glove that can capture finger-bending values. Additionally, we believe that recognition rate can be improved by using more advanced filtering techniques and by deploying an online filtering mechanism for captured motion data. Utilizing cheaper and more comfortable motion capture approaches like Wii$^{\text{TM}}$, Kinect$^{\text{TM}}$, inertial sensors or computer vision can also be a significant improvement to the proposed algorithm.

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