Evaluation of Virtual Product and Usability of Haptic Feedback Systems

(A case study of Phantom Omni force feedback device)

A thesis submitted

in partial fulfillment of the requirement for the award of the Degree of

Doctor of Philosophy

by

Hailu Gebretsadik Teklemariam

Department of Design
Indian institute of Technology Guwahati
Guwahati-781039, Assam, India

Evaluation of Virtual Product and Usability of Haptic Feedback Systems

(A case study of Phantom Omni force feedback device)

A thesis submitted in partial fulfillment of the requirement for the award of the Degree of Doctor of Philosophy

By

Hailu Gebretsadik
Roll No: 126105008

Under the Supervision of

Prof. Amarendra Kumar Das, PhD

Department of Design

Indian institute of Technology Guwahati

Guwahati-781039, Assam, India

2016

TH-1503_126105008

DECLARATION

It is certified that the work contained in this thesis entitled "Evaluation of Virtual Product and Usability of Haptic Feedback Systems - A case study of Phantom Omni force feedback device" has been carried out by me, a student in the Department of Design, Indian Institute of Technology Guwahati (IITG), Assam, India under the guidance of Prof. Amarendra. Kumar Das for the award of Doctor of Philosophy. This work has not been submitted elsewhere for a degree.

Hailu Gebretsadik
Department of Design
Indian Institute of Technology Guwahati
Guwahati - 781 039
Assam, India

ute of Technology

Place: Guwahati
Date:

TH-1503_126105008

CERTIFCATE

The research work presented in this thesis entitled “Evaluation of Virtual Product and Usability of Haptic Feedback Systems - A case study of Phantom Omni force feedback device)” submitted by Mr. Hailu Gebretsadik Teklemariam to the Indian institute of technology Guwahati, Assam, India for the award of the degree of Doctor of Philosophy has been carried out under my supervision. This work has not been submitted for the award of any other degree or diploma to this institute or to any other institute or university. He has also fulfilled all the requirements including mandatory coursework as per the rules and regulations for the award of the degree of Doctor of Philosophy of Indian Institute of Technology Guwahati.

Prof. Amarendra. Kumar Das
Supervisor, Department of Design
Indian Institute of Technology Guwahati
Guwahati - 781 039
Assam, India

of Techno

Place: Guwahati

Date:

TH-1503_126105008

Acknowledgements

I will like to express my utmost appreciation to my supervisor Prof. Amarendra Kumar Das, for his continued support, encouragement and guidance from the very early in the direction of my research, giving valuable advice for my thesis and facilitating me to get advanced hardware devices that support my work and tying up visit to Marco Polo Product Pvt. Ltd., Kolkata.

I also like to thank Mark Dixon at SenseGraphics for his support at H3D.org forum. I would like to thank Prof. Tiwari Rajiv for allowing me to work and use the facility of vibration and acoustics lab. I will like to express my deep sense of gratitude and profound thanks to the members of doctoral committee Prof. Debkumar Chakrabarti, Dr. Sougata Karmakar of Department of Design, IIT Guwahati and Dr. Siser Kumar Nayak, Department of Electronics and Electrical Engineering, IIT Guwahati for their valuable comment, guidance and suggestion which helped me to grow during my State of Art and Progress seminars. Furthermore, during the period of the study, 84 students participated in the testing of virtual model and usability study of haptics device (Phantom Omni), and I am very thankful to all design and mechanical engineering students for your time and comments. The valuable help of Department of Design faculty, staff and PhD colleagues is also appreciated.

I am grateful to my family, my wife Lemlem Berhe. and my daughter Hiyab Hailu, for their patience, and moral support which was needed throughout this study. Finally, I like to extend my appreciation and gratitude to Collage of Engineering, Defence University, Ethiopia for undeviating support without which this research would not have been pursued.

Date: Hailu Gebretsadik

IIT Guwahati

TH-1503_126105008

Abstract

Research towards a methodology which helps designers/engineers in conceptualizing, facilitating participatory design and validating products during designing and development process becoming more important with the aim of reducing the lengthy process and errors that crops up during the process. It has also been realised that today's technology is having more influence in education than it had earlier. Although, during product design and development, products virtually prototyped in CAD environment is being realized through rapid prototyping and tooling, but it is felt that in absence of sensual/haptic feeling and perception of size, form in CAD prior to rapid prototyping, products realized still require modification. In this kind of situation, integration of virtual reality with haptic is among the solutions to avoid repeated physical prototyping as well as rapid prototyping and reduces related cost. This integrated system of virtual reality-haptic feedback interaction may enhance the usability evaluation of virtual products by replacing the physical mockups with digital mockup thereby reducing the development time and the costs of product design. Therefore, emphasis of this research was to evaluate the usability of PHANToM Omni™ force feedback device towards perception of the products' shape, depth, texture, and weight - some of the essential features of a product. During this process it was attempted to study the virtual and augmented reality, haptics working principles and their advantage towards product evaluation using PHANToM Omni™ force feedback device. Through this study it was possible to understand the working principles of haptic device and write codes/program using OpenHaptics software development toolkit in order to manipulate the virtual object which was prepared through CAD Software (in this research CATIA was used), thereafter, experimental setup with full system were established. After preparing questionnaires and virtual reality-haptic system, participants were allowed to manipulate the virtual object via PHANToM Omni™ haptic feedback device and compare the physical properties of different virtual objects. Finally collected data analyzed and result revealed the potential of integration of virtual reality-haptic system for realizing the virtual object's surface texture, size, shape, and weight. But, as the participants revealed on

TH-1503_126105008

their feedback that the original stylus of the haptic device was not comfortable and caused pain during weight perception and attempt has been made to design and change the existing stylus considering the standard gripping dimension and finally experiment conducted to evaluate the designed version of the stylus.

Keywords: *Phantom Omni, haptics, virtual object, virtual reality, augmented reality, product design, CAD.*

TH-1503_126105008

CONTENT OF THE THESIS

TH-1503_126105008

TH-1503_126105008

TH-1503_126105008

TH-1503_126105008

List of figures

TH-1503_126105008

TH-1503_126105008

TH-1503_126105008

List of tables

TH-1503_126105008

TH-1503_126105008

TH-1503_126105008

Nomenclature

2D	Two-Dimensional
3D	Three-Dimensional
RP	Rapid Prototyping
VP	Virtual Prototyping
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
API	Application Programming Interface
RPT	Rapid prototyping technology
VR	Virtual Reality
AR	Augmented Reality
VRML	Virtual Reality modeling Language
XML	eXtensible Markup Language
X3D	eXtensible 3D
H3DAPI	Haptic 3D Application Programming Interface
OpenGL	Open Graphics Library
PHANToM	Personal HAptic iNTerface Mechanism
SUS	System Usability Scale
PEoU	Perceived Ease of Use
PU	Perceived Usefulness
SU	System usability
SRoP	System roughness perceptions
SStP	System stiffness perception
SWghtP	System weight perceptions
SShP	System 3D shape perceptions
RQ	Research question
DV	Dependent variables
IV	Independent variables

TH-1503_126105008

CHAPTER 1

1.0. Introduction

1.1 Background

There has been tremendous advancement of Computer Aided Design (CAD) and related technology in last few decades and competitions among industries, consumers' attitudes and current 'Industrial Design' and 'Engineering Design' students' higher expectations from academic institutions became a challenge to the industries and academic institutes respectively; this challenge forced academic institutions and companies/industries to seek better design methodology and production process in order to satisfy their customers/users and stay in the competitive market. During this attempt to come up with the best solution and approach, designers and manufacturers may face problem in understanding the users' interest or deploying correctly user based specification in their concept design.

In product design and development processes, there are critical stages which determine the final product success. Errors in this critical stage may cause inability to perform in the competitive market due to overall product expense. As depicted in **Figure 1.1**, a product design and development process starts with the identification of the customers' needs from all aspects followed by concept development, and deepen to component and system level design and manufacturing requirements. In this product design and development processes, during the conceptual design, it is critical to evaluate and select the conceptual product model that meets the expectations from customers, and after detail design, it is also required to test and evaluate the physical product. If it is not as per the requirement, it may lead to redesign/modification and repeated prototype. In order to avoid this repeated prototyping cost and to have clear cut perception, it is important to deploy virtual reality–haptics integrated evaluation technique. During this period, it is also important to allow participation of stakeholders (customers, manufacturers, end users) to participate and give their feedback regarding the product in order to come up with the best and competitive

TH-1503_126105008

product features. Haptic in VR simulation is a growing research area for a wide domain of engineering application.

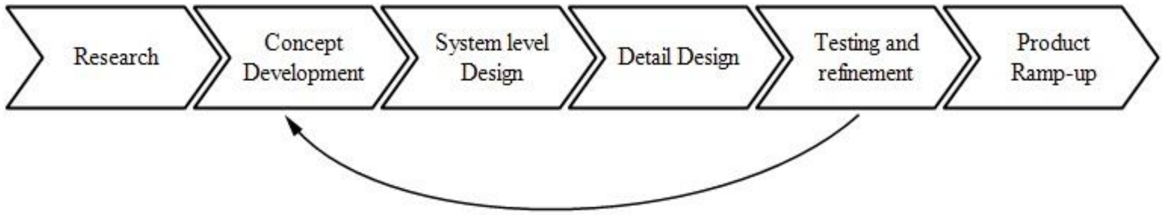


Figure 1.1: Product Development Process, adopted from (Ulrich, 2003)

In general, as indicated by different researches, the first 15 to 20 % of design process which is conceptual stage, can determine the remaining 70% to 80% of cost of design. This means major design decision may fall in this 15 to 20% in order to reduce overall cost of design process (Sabater et al., 2008; Tangram Technology Ltd., 1998; Ullman, 2010)**.** As shown in **Figure 1.2**, the cost of fixing error increases as time goes during product design. Due to this reason, at the development stage of products, companies prefer exploiting different technologies that help in product realization process, testing and analyze the usability of product and evaluation without building the physical prototype and environment.

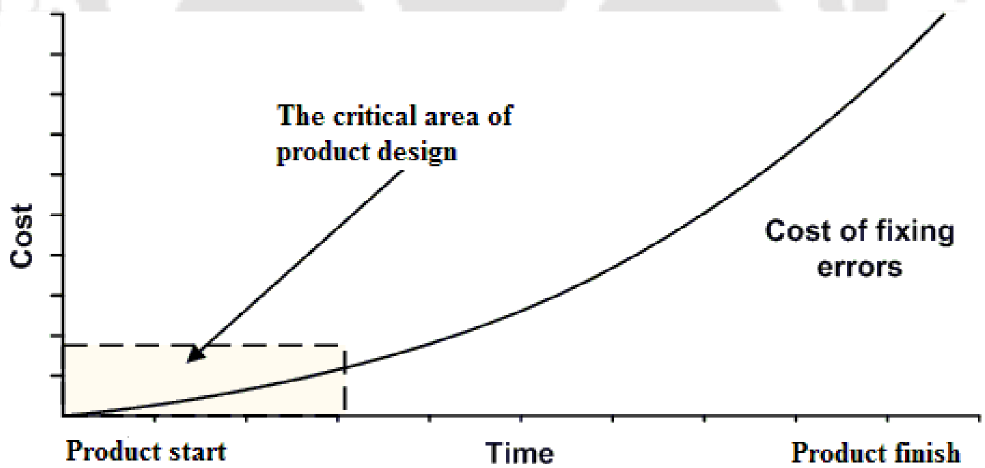


Figure 1.2: Cost of fixing error during product design, adopted from (Tangram Technology Ltd., 1998)

Virtual reality techniques have significant role in qualifying the level of user satisfaction, effectiveness and efficiency of the product and workstation to the human

TH-1503_126105008

standard. Moreover, virtual reality integrated with haptic devices can give new perspective and understanding of various concept and phenomena, as well as high fidelity and allows interaction (tactile and sensing) between the user and a solid virtual object in addition to the visual inspection, since haptic support a bidirectional flow of information (Gao, Wang, & Jiang, 2012; Hailu Gebretsadik & A. K. Das, 2014; Mikropoulos & Natsis, 2011).

These can be meaningful and acceptable by implementing mechanical (weight, elasticity, etc.), ergonomic properties/characteristics and factors that has to be considered at each activity and imitating the real behavior and attribute of working environment, working process, and production process. There are commercial simulation software integrating an established ergonomics work process into a virtual environment available. This kind of simulation software may give and show the impact on the human with some rough calculations; this doesn't reflect the actual feeling - a key factor to conduct an efficient and reliable evaluation at early stage of a design process (Etheredge, Kunst, & Sanders, 2013). This is the reason why haptic found an outstanding development in different disciplines.

1.2 Motivation

The following are the motivation for undertaking the research.

- Reducing the overall cost in the early stage is the preferable and critical solution as shown **Figure 1.2**. This might be achieved by inducting appropriate technology that helps in thorough evaluation in the early stage of design process.
- Research gaps observed in literatures (mentioned in literature review section 2.6) needs to be filled through conducting further research.
- Increase the realization of product process work and to reduce the expense in product design and development,
- To utilize additional sensory inputs/outputs in addition to the visual perception that are very important and is capable of simultaneous input and output,
- To widen the scope of haptic technology for use by the designers/engineers, and also for academic purpose.

TH-1503_126105008

- To investigate the usability testing of force feedback device (PHANToM Omni™) for user accessibility which may be essential.

1.3 Statement of the problem

During product design and development process, the cost of error fixing is expensive through physical prototyping route. Investigating the potential of virtual reality, application of virtual reality and virtual prototype evaluation using force feedback technology could be a solution to reduce the cost. Furthermore, usability testing of force feedback device for user accessibility is also essential.

1.4 Research Questions

From the above study, questions were formulated in order to define and delineate the research problem clearly.

- How productivity can be enhanced in the design phase of the product development through virtual reality system?
- How users feel about the CAD-virtual reality performance?
- How the haptic interaction scenario and its physics are related with performance of users in virtual reality environment implemented with the haptic feedback system?
- How a user feels about virtual prototyped product and how virtual prototyped product can be manipulated with hand; evaluate the product efficiencies and ease of use.
    - Sense of realism
    - Accuracy
    - Ease of interaction, etc.
- Is the haptic device user centric?

1.5 Aim and objectives

Aim:

Evaluation of virtual product and usability of haptic feedback systems considering use of PHANToM Omni™ force feedback device as a case study.

TH-1503_126105008

The overall objectives of the present research conducted for this dissertation is to;

- Integrate virtual reality with haptic devices in product design and in doing so,
- Analyze and identify usability related problems associated to PHANToM Omni™ during properties of virtual product evaluations through open source libraries H3D.
- Formulate and implement solution(s) for usability related problems of haptic device.
- Understand the user perception towards the virtual object (such as oil bottle, water jar, mobile apparatus) through a set of experiment considering surface texture, depth, stiffness, 3D form and weight perception.
- Evaluation the feasibility of using a desktop haptic virtual environment as a design tool for study of weight of tea leaf plucking model taken as a case study:

In an effort to address this aim and objectives, three primary research hypothesis were developed and are described below.

1.6 Research Hypothesis

H_{01} – Virtual reality-haptic feedback device integration will improve the product design and development process duration.

H_{02} – If the technology can provide other sensory inputs in addition to the visual perception the productivity of designers will enhance.

H_{03} – Force feedback device (PHANToM Omni™) may give perfect touch feeling and its stylus comfortable to all parameters such as weight, shape, texture, stiffness perception.

1.7 Scope of the study

The present study focuses on the usability of the haptic device (PHANToM Omni™) in an attempt to enhance evaluation of virtual prototyping. Virtual products such as oil bottle, water bottle, water jar, carpet, mobile phone and tea leaf plucking machine were considered. The generated haptic product tactile properties are limited to surface texture (smoothness/roughness), hardness/stiffness, weight, and 3D form perception.

TH-1503_126105008

Furthermore, attempt has been made to realize hidden holes passage by giving the same size diameter of sphere and move through the hole. Finally, to come up with a better and more accessible PHANToM Omni™ stylus to users.

1.8 Limitations of the research

Every research has its own limitations. In this research too there are limitations which are:

1. During data collection, limitations of Workspace and rendering force (3.3N) was observed.
2. Due to the lack of comprehensive research set up comprising different types of haptic devices currently available in the market coupled with computer having high performance compatible with haptic device, in this study only PHANToM Omni™ haptic feedback device was used to interact with the virtual object.

Other than the above, various limitations faced during the research that can be attributed to system limitation of the research are:

1. The data transfer capabilities of IEEE1394 Fire wire card were bottleneck.
2. Models were represented with finite element and during rendering it was observed that computational time is more when it is highly meshed i.e. refreshment rate (frame rate per second) is low. This was observed when all the triangles transferred to the haptics loop.
3. During deformability evaluation of different bottles, it was challenging to get smooth visual and smooth force feedback, this may be due to the performance of computer graphics card.
4. The X3D data when converted from STP file format to X3D there might be some discrepancies that lead to the irregularities. (due to the geometric node patterns e.g. IndexedFaceSet) and it was observed that IndexedFaceSet is slower to render than IndexedTriAngleSet
5. Problems in haptic surface touching (fall through) were persistently happened, and this may be due to the following reasons.

TH-1503_126105008

- ✓ Tiny holes in the mesh which are hard to see, but which point-proxy haptics algorithm will fall through.
- ✓ Discontinuities in the shape of the surface, due to the mesh compatibility on each nodes of the finite element.

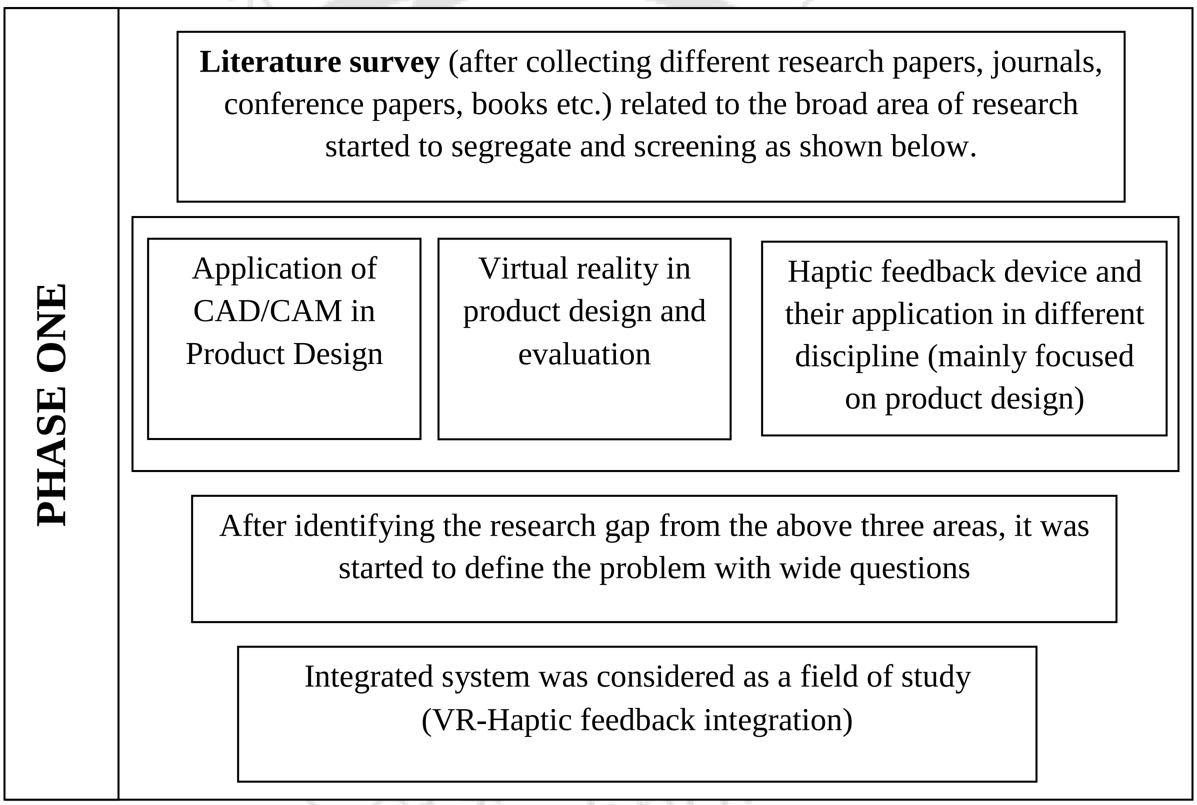
1.9 Methods and overall flow of the research

In this research, initially state of the art in VR application was studied through several research articles, review papers, books and chapters from various authentic search engine with the help of internet as well as published books and journals. The search engines used for this present review include Google Scholar, Taylor & Francis online, ACM digital library, IEEE Xplorer, Science Direct, Springer and other digital libraries.

After thoroughly understanding different literature and analyzing existing research gaps, research activities were continued by studying the impact of product colors on users' shape perception, how scene graph is constructed, rigid body define (physical law) and understanding different programing (C, Python), open source code, demo application and theories related to virtual reality and haptic feedback systems. Thereafter, the way the 3D Model converted to X3D, define the nodes, fields, etc. and haptic surface creation were studied. Based on the study, experiments were conducted to validate the hypothesis by actually creating virtual prototype in CAD model (different 3D objects such as water bottle, water jar, mobile phones apparatus, penholder, and tea leaf plucking machine using CATIA and later converted to X3D data format), exporting to virtual environment and evaluating and improving the design prior to actual prototyping. During this period effort has been made to rectify the problem where existed in understanding the programming through involvement in H3D.org forum. Finally, the usability of haptic feedback device (PHANToM Omni™) and virtual prototype has been tested and realized the surface texture, stiffness, 3D shape and the weight by 84 subjects (students); and results analyzed and inferences were drawn from the results. In this thesis the descriptive statistics, such as means and standard deviation as well as the test statistics, obtained value of the test

TH-1503_126105008

and the probability of acceptance of the null hypothesis has been reported. During the usability of PHANToM Omni™ testing, participants reported their discomfort and pain/strain felt in gripping the stylus during virtual weight lifting. Finally, based on the feedback of participants, the stylus was designed and prototyped; modified stylus that fitted over the original stylus, with the aim of increasing the gripping comfort and reduce pain in the participants' wrist and improve task precision and efficiency. Throughout the data analysis, SPSS (Statistical Packages for Social Sciences) were used as a statistical tool.



TH-1503_126105008

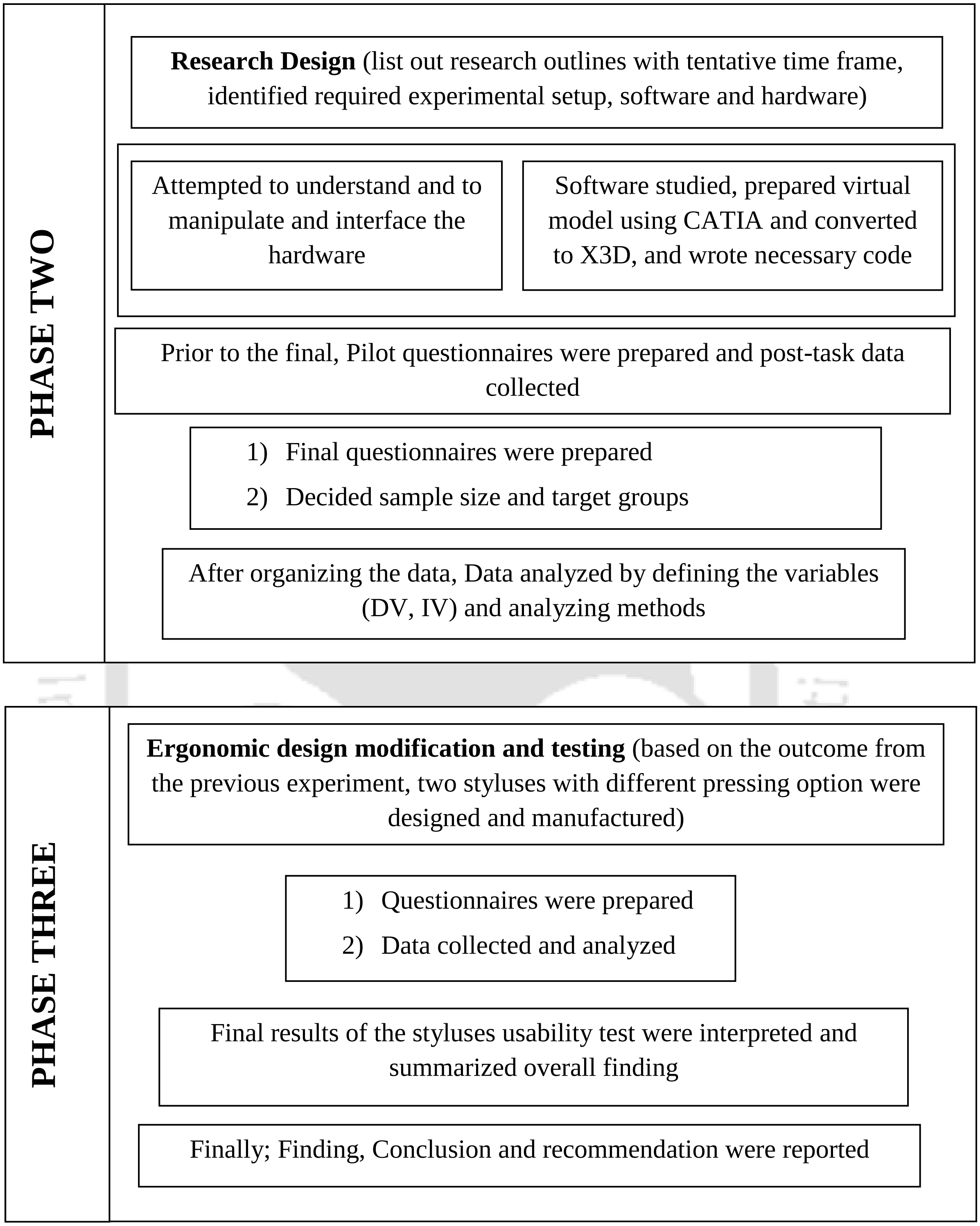


Figure 1.3: Flow of the research work

TH-1503_126105008

1.10 Contribution of the research

This thesis can contribute in creating awareness towards the implementation of VR-haptic integration for usability evaluation during the design and development phases and design education for realization and understanding the abstract theory which is not easy to understand. It also recommended modification of the existing stylus and actually modified the handle/stylus of the haptic device to be easy and comfortable to use for weight perception that was difficult and tiring during initial experiment.

1.11 Outline of the Thesis

This thesis is structured into six chapters as described below.

Chapter 1 contains an overview of the research highlighting the motivations, aim and objectives, research questions that needs to be answered the research hypothesis, methods and flow of the research, the scope and limitation of the study, as well as the contribution of the thesis.

Chapter 2 contains literature review related to virtual reality, augmented reality, virtual prototyping, rapid prototyping, virtual reality and augmented reality applications and their contribution in day to day life of a human being such as in education, health, military, automobile industry and ergonomics disciplines. The research gaps that was identified as a broad area of the research is also covered. Finally, what it means by usability and usability evaluations related to this research are discussed.

Chapter 3 contains discussion on the reviewed literature related to human haptic system (sensory system) and how it is replicated to the real world application with its working principle. Discussion related to haptic integration with virtual object and their applications in education, health, ergonomics, military, product design were considered.

Chapter 4 describes regarding the experimental setup, methodology, data collection, data analysis and inference against the hypothesis. Finally, usability testing results regarding human perception with respect to haptic shape, texture, weight and the ability of the device in giving the haptic feeling and its usability are discussed.

TH-1503_126105008

In **Chapter 5**, discussion regarding the design modification of the stylus, its prototyping based on the feedback of participants' on the original stylus has been covered. Finally, usability testing results regarding its easiness and comfortability to grip are also discussed.

Chapter 6 consists of discussions on the overall process and usability testing results of the three styluses i.e. the modified styluses Vs. the original stylus. Thereafter discussion regarding various limitations faced during the research due to system setup and due to the department research set up is mentioned. Finally, findings and contribution of the research, conclusion and recommendation has been provided.

TH-1503_126105008

CHAPTER 2

2.0. Virtual Reality, Augmented Reality, Virtual Prototyping and their applications

2.1. Virtual Reality and allied systems

As stated by various authors, (Abulrub et al., 2011; Anderson, Ma & Poyade, 2014; Gosselin et al., 2013; Lele, 2013; Onyesolu, Ezeani & Okonkwo, 2012; Onyesolu & Eze, 2011; Parsons & Trost, 2014; Pungotra, 2012; Seth, Su, & Vance, 2005; Teklemariam, Kakati, & Das, 2014; Ullman, 2010; Xia et al., 2012),virtual reality has become a state of art technology in the fields of Industrial design, manufacturing, textile, architectural design, military, automotive and aerospace design, medical, education and entertainment. The purposes being varied such as virtual object realization, training, usability evaluation, simulation, analysis and optimization of manufacturing processes and identifying issues related to the assembly sequences.

2.1.1. Virtual reality

Virtual reality has been defined by different authors in different ways with the context of use. Among those definitions, it may be better to mention the commonly used definitions. Virtual reality is a technology which is often regarded as a natural extension to 3D computer graphics with advanced input and output devices (Jayaram, Connacher & Lyons, 1997). virtual reality defined according to Sherman & Craig, (2002) as a medium composed of interactive computer simulations that sense the participant's position and actions and replace or augment the feedback to one or more sense, giving the feeling of being mentally immersed or present in the simulation (a virtual world). Virtual reality can give the real-time interaction (immersion) and feeling of presence in the generated environment that substitute real world with a digital reconstruction through several communication technologies such as Head Mounted Displays (HMD), body tracker, or other devices. This allows carrying out activities as shown in **Figure 2.1** used for assembly and disassembly demonstration using body tracker and in **Figure 2.2** Ford company used to inspect the appearance

TH-1503_126105008

and ergonomic placement of interior controls. The disadvantage of wearing HMD for prolonged time, such as headache, dizziness and nausea has been mentioned by Nee et al, (2012). According to various authors (Aziz et al., 2015; Fällman, Backman & Holmlund, 1999; Li, Khoo & Tor, 2003; Winn, 1993) Virtual reality is categorized in three different system based on the sense of immersion or degree of presence:

First is desktop virtual reality systems that uses conventional display screens with stereoscopic glasses to enhance the visual depth and observe 3-Dimensional objects as immersive virtual reality systems and this is most preferable type virtual reality system due to its ease of use, installation, and least expensive form of virtual reality.

Second is a semi-immersive virtual reality system that attempts to give the users a feeling of being at least slightly immersed by a virtual environment. This means users still can see himself and the other users. Images are displayed based on the main user's head position and orientation provided by a head tracker etc.

Third form of virtual reality is usually referred to as being fully immersed. Immersive virtual environment typically use a head mounted display or projection based display systems, wired gloves, position tracker devices or other devices that attempts to isolate the user from the real world in order to increase the realism of the simulation. It is also possible to exploit and increase immersive experience perceived by users by providing haptic system to the virtual environment. In this research, more focus has been given for desktop based virtual reality.

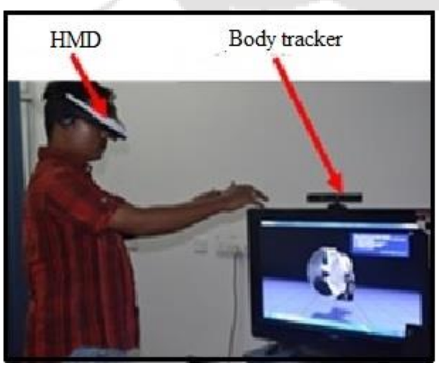


Figure 2.1: VR in assembly and disassembly demonstration [IITG CET Lab].

Figure 2.2: Ford's immersive vehicle Environment **(**Sherrice Gilsbach, (2014)

TH-1503_126105008

2.1.2. Augmented Reality

Augmented reality is a technology, which seeks to enhance the virtual reality environment by integrating the real world with added virtual elements with the aim of improving the users' feeling of presence and due to this reason sometimes in some books and report it is called as an enhanced immersive virtual reality system. These can include sounds, sensations, or images generated by a computer system. Augmented reality brings virtual information or object to any indirect view of user's real world environment to enhance the user's perception and interaction with the real world (Kesim & Ozarslan, 2012). It is shown in **Figure 2.3** augmented reality application in education to enhance teaching by enabling the students to visualize and interact, and **Figure 2.4** shows augmented reality application in automobile industry (BMW) to carry out engine maintenance with the help of the goggles which is integrated with earphones.

Figure 2.3: Augmented reality in a printing media (inglobe, 2011)

Figure 2.4: Augmented Reality in Automotive Industry **(**Augmented Reality introduction, 2007)

2.1.3. Virtual Prototyping

It is process of getting digital output (computer generated geometrical shapes) that represents the imagined/anticipated model of component or system to be constructed during design processes. Virtual prototyping technology is widely used in many cutting edge design led industries and universities and being utilized to bridge the gaps between conceived products that in the imagination of the designer and real problems of teaching

TH-1503_126105008

theory and application. It starts from a construction of geometric models of products, which are then used for conducting aesthetical analysis, ergonomics evaluation, functional aspect and simulating the component manufacturing, understanding the manufacturing or assembly process. Virtual Prototyping (VP) involves Computer Aided Design (CAD) and Computer Aided Engineering (CAE) software for validating (strength, functionality and ergonomics) prior to the physical prototype. VP has great advantage for decision making and modifying the shortcomings during the design stage without production of physical prototypes. The use of physical prototypes is more expensive, these take longer to finish and difficult or impossible to modify it (Arbeláez-Estrada & Osorio-Gómez, 2013; Ye et al., 2007).

2.1.4. Rapid Prototyping

Conventional design ideologies require that engineers construct a variety of physical prototypes to test and evaluate design concepts. Due to the nature of such a process, the design and analysis of new products can become very time consuming and expensive. Therefore, a traditional product design approach often takes very long product development time. Currently, new technologies involving rapid and virtual prototyping are revolutionizing the way products are designed and realized. Rapid Prototyping (RP) is the technology that helps companies quickly fabricate any complex shape, reduce the cycle of product development, reduction of waste, and also facilitate to make design improvements earlier in the process where changes are required. RP used different techniques such as Stereolithography (SLA), Laminated Object Manufacturing (LOM), selective laser sintering (SLS), fused deposition modeling (FDM), 3D printing etc. to manufacture real model with the support of 3D CAD/CAM software. RP is the best example of the current technology for changing the traditional product development process and widely used in industry for visualizing the product form, aesthetic evaluation, assembly and disassembly, and in general as a validating tool. It is an important tool to support any research tasks that requires prototype with a wide range of material and precision. It is widely used specifically in health science and biomechanical engineering sector for generating models for tissue replacement, bio devices and preparing training module using biological materials (Lantada & Morgado, 2012; Peltola et al., 2008).

TH-1503_126105008

However, models generated through RP can only be inspected visually and evaluated after physical prototyping. Due to these reason manufacturers are forced to re-prototype in order to correct any error that may have occurred. This leads to introduction of haptic feedback device in the evaluation of virtual object before it is prototyped as physical ones.

Figure 2.5: Sample product prototyped using rapid prototyping technology
Source: Fine Mechanics and Product Analysis lab. IITG

2.2. Application of VR and AR in design related fields

There is no doubt that use of VR technology has brought avant-garde changes in many multidisciplinary scientific fields including design education. Large number of the authors have agreed that VR and AR are important and has potential in visualizing and interacting abstract model in three dimensional contexts and to facilitate learning. VR/AR provides the natural and interactive ways to express ideas and overcome the technical gap in the iterative design process by upgrading from traditional computer aided design process to mixed reality aided design space (Ran & Wang, 2011). In addition to this, Ye et al, (2007) investigation and exploration were carried out to establish the potential of VR based technologies into a computer aided product design and evaluation in comparison with traditional techniques. The use of VR applications in various design education related fields have improved the productivity of teaching and training by allowing engineers to apply theoretical knowledge to real industrial problems with real time experience (Abulrub et al., 2011; Pantelidis, 2010; Teklemariam & Das, 2015). Nowadays applications of AR are widely used. Unlike other computing technologies, AR

TH-1503_126105008

supplements (combines) the real world with virtual objects (i.e. computer-generated) (Furht, 2011). The combination of AR technology with the educational content creates new type of automated applications which acts to enhance the effectiveness and attractiveness of teaching and learning process for students in real life scenarios. Actually, AR is a new medium which is combining aspects from ubiquitous computing, tangible computing and social computing. This medium offers unique affordances, combining physical and virtual worlds, with continuous and implicit user control point of view and interactivity (Kesim & Ozarslan, 2012). Using AR systems, learners interact with the 3D information, objects and events from different points of view in a natural way. Billinghurst, (2002) used AR technology in education for support of seamless interaction between real and virtual environments and suggested educator to work with researcher in exploring how this can be applied in school environment. Another interesting application of AR technology is to develop augmented reality textbooks (Kesim & Ozarslan, 2012), in which books are printed normally but when a webcam is pointed over the book, it brings visualizations and designed interactions on the screen of the device. This is possible by installing special software on a computer or mobile apps on a portable device. This technology allows any existing book to be developed into an augmented reality edition after publication. Through the use of AR in printed book pages, textbooks became dynamic sources of information. In this way, people can have a rich interactive experience with comparatively less computer knowledge than computer experts.

2.3. Application of VR/AR-Haptic in ergonomics

Products are used by different level of users on a daily basis, regardless of its complexity. The main and decisive criteria focuses on meeting user expectations and needs in a safe, efficient and pleasurable way. To do so, it is important to evaluate the product in component or system level before it goes for final prototyping. In this context ergonomics focus on the study of the interaction of human with products, and the intervention of VR-haptics may help in allowing users to sense the product considering its impact on physical, cognitive, and other relevant factors. With the existing digital human modeling

TH-1503_126105008

(DHM) and virtual human simulations software (such as RAMSIS, EAI Jack, BHMS and 3DSSPP) there are possibilities to evaluate and validate using mannequins embodying the anthropometric data; but it is complex and time consuming. Therefore, the use of virtual prototypes augmented with the physical interaction has better potential to do as proposed (Bordegoni, Colombo & Formentini, 2006) and demonstrated in **Figure 2.6** for evaluating the Ergonomics of control boards that used to manipulate virtual knobs, buttons and slide bars. In addition to this, to mention a few of the applications, there are possibility to measure the muscle strength (muscle force) with electromyography (EMG) using virtual object having the load being felt in users' hand. This has been implemented during this research by studying the appropriate anatomy (specified muscle) and placing the electrode/sensors as shown in **Figure 2.7**. In addition to this as stated by Arroyave et al, (2014), VR/AR has potential advantage to infer possible ergonomics issues related to manual assembly process in real-time during product conceptualization using augmented reality based modelling tools. **Figure 2.8** shows ergonomic analysis intervention approach during conceptual design. This may allow saving resources during design process and increase quality, operators comfort, health, and productivity.

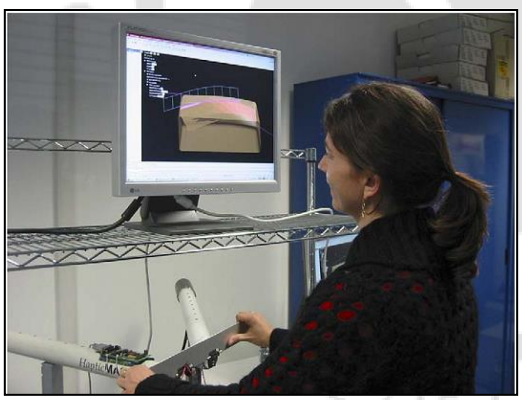


Figure 2.6: Haptics in ergonomics validation (Bordegoni et al., 2006)

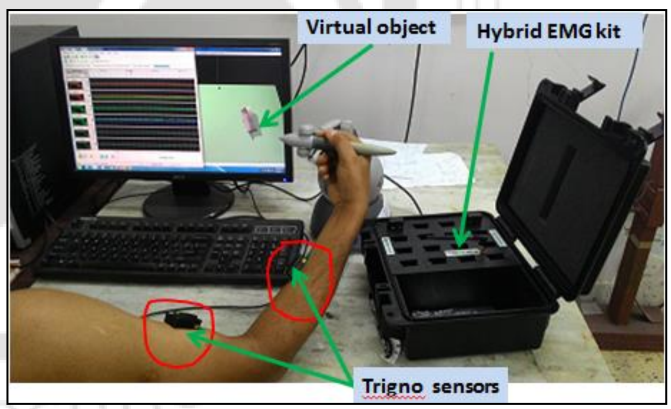


Figure 2.7: Muscle force measuring with electromyography (EMG)
Source: Ergonomics Lab, IITG

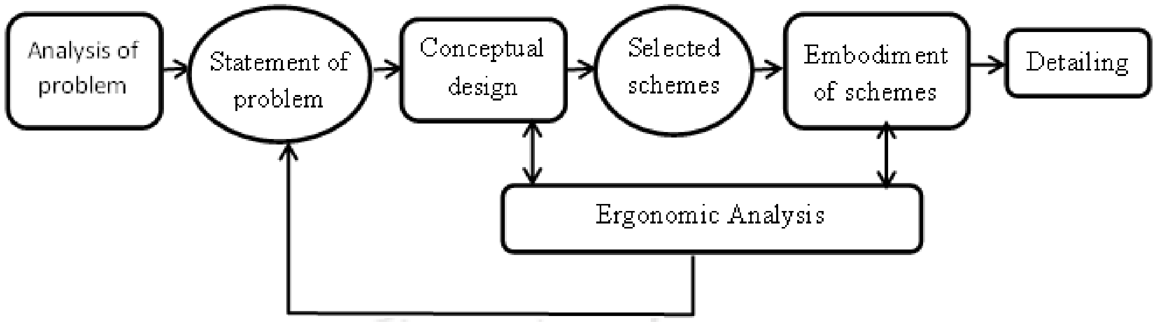


Figure 2.8: Intervention of ergonomic analysis in product evaluation (Arroyave et al., 2014)

2.4. Application of VR-Haptic in health sector

As it is mentioned at the introduction of this chapter virtual reality is used in the health sector for different purposes. To mention some of its application in facilitating the training of novice medical personnel and senior doctors such as surgeons, one can plan and rehearse by operating on a virtual patient model with life like tissues' reaction as it is shown in **Figure 2.9**. As shown in **Figure 2.10**, it is also used as a dental simulation with force feedback that allows students to familiarize with root canal surgery procedures with realistic feeling. Furthermore, as shown in **Figure 2.11** haptic feedback device and haptic scissors were used to simulate the virtual feeling of cutting a human liver. This technology gives the opportunity to avoid use of volunteer patient or cadavers for training. Furthermore, the system may give the opportunity for appropriate assessment of medical students' skills during their study; however, this may require increase in the level of realism to achieve.

TH-1503_126105008

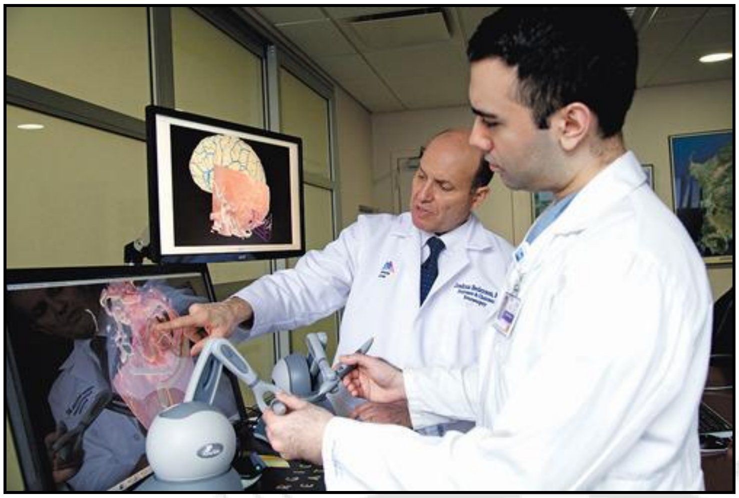


Figure 2.9: Virtual reality simulation ("VR and Medical Training," 2014)

Figure 2.10: Root canal surgery (Liu & Laycock, 2010)

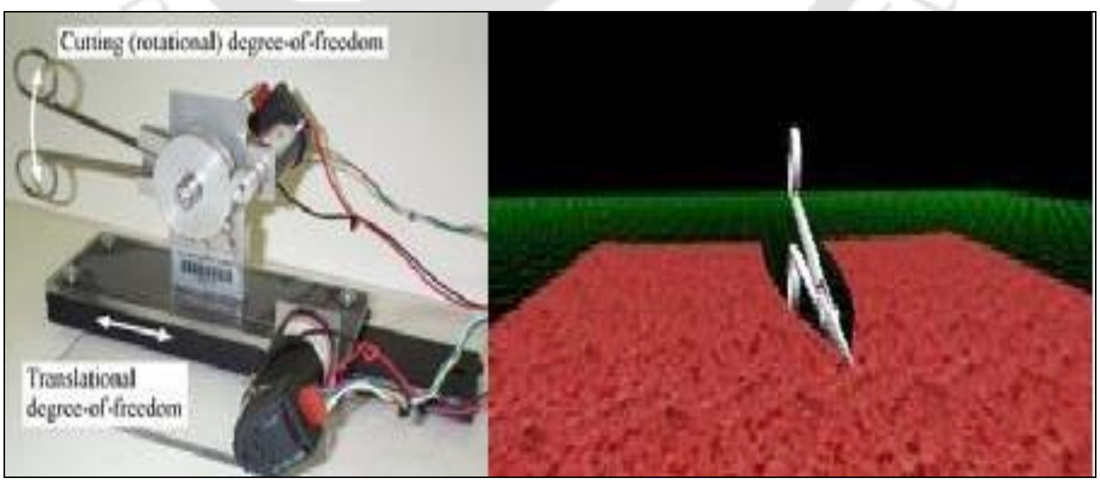


Figure 2.11: Haptic scissors cutting simulated liver tissue (Christophe Grujon, 2008)

TH-1503_126105008

2.5. Application of VR-Haptic in military application

VR-haptic system is already widely used for all wings of defense sector applications (Lele, 2013; Lindeman et al., 2004). VR is used from planning the combat situation in advance to training purpose such as to devise strategy to fight with enemy in a complicated environment. This may be used by representing the equipment used during war time, actual environment with fully or partial virtual environment such as representation of digital sand table with necessary human's models, vehicles and fighter aircraft for war game and head mounted displays with an inbuilt system. During training, trainers may come from different background with no experience of how to handle the weapons, therefore injuries may happen during exercise because of the ammunition or due to some other circumstance related to the actual use of machine gun (Immonen, 2008). In this scenarios haptics may play an important role in reducing risks and cost of ammunition. This means integration of haptics with the virtual environment may increase the realism as the actual war field phenomena. In addition to this, the Virtual reality to haptics integration is important for aeronautical, vehicle assembly/disassembly or maintenance training for a number of trainers in a limited space and less cost without deploying physical aircraft or vehicle in a spot. **Figure 2.12, Figure 2.13** and **Figure 2.14** are highlight of its application in different military fields.

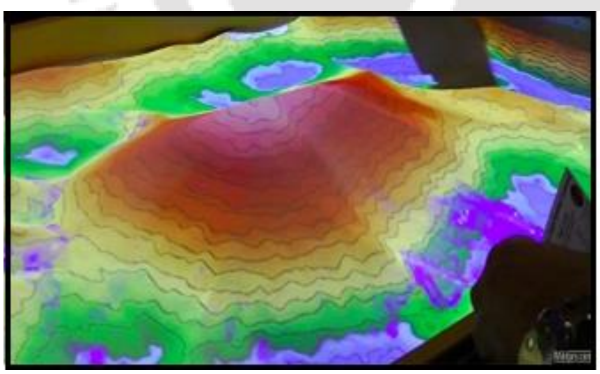


Figure 2.12: Digital landscape ("Touchscreen Landscapes," 2014)

Figure 2.13: Virtual reality trainer used for STRIGER crew training (Cassidian - Virtual Military Training Systems, 2012)

TH-1503_126105008

Figure 2.14: Virtual reality system in military training (Lindeman et al., 2004)

2.6. Research gaps

In general, different researcher has shown their appreciation and their excitement on the application of the VR-haptics feedback systems in all disciplines/fields of application, and attempted to address the drawback and mitigate regarding the haptic feedback device, and haptic rendering algorithms. Some available literature is mentioned below:

Laycock & Day in their survey have explained the suitableness and capability of haptic rendering algorithms for desktop force feedback devices such as PHANToM Omni™, phantom desktop, etc. of SensAble technology products for overall techniques of simulating surface properties; and also figured out problems associated with the haptic rendering algorithms and attempted to alleviate the issues by developing tool based haptic rendering for single point contact (Laycock & Day, 2007).

Howard & Vance have investigated the feasibility of an affordable haptic desktop Virtual reality system for assembly operation purpose (Howard & Vance, 2007). During their research, they used several software packages including VR Juggler, OPAL/ODE, OpenHaptics™, and OpenGL/GLM to explore the benefits and limitations of combining physically based modelling with haptic force feedback. Finally, after using the

TH-1503_126105008

application with different scenario they have come up with some conclusions that can be drawn about the system as a means for evaluating assembly operations and the tools used to create it. In their study they have given more focus on the capacity of ODE (open dynamics engine) testing the detection collision for primitive to primitive, primitive to mesh and mesh to mesh collisions during assembly operation of multi part object.

Ang, Horan, Najdovski, & Nahavandi have introduced a gripper attachment that provide multipoint haptic feedback to a user's individual fingers (Ang, Horan, Najdovski, & Nahavandi, 2011), and the device is shown in **Figure 2.15**. The approach employs two PHANToM Omni™ haptic devices to independently render forces to the user's thumb and other fingers. Compared with more complex approaches to multi-point haptics, as they mentioned in their paper this approach may provide a number of advantages including low-cost, reliability and ease of programming. In addition to this it also discussed, the gripper's ability to accurately control over the rotation of the grasped object about the grasp axis, but in this paper they have tried to grip and evaluate three contact models (frictionless, frictional and soft) of virtual cubes using CHAI3D.

Research gap identified: in above research, the authors didn't go for other parameters such as shape, weight perception etc…

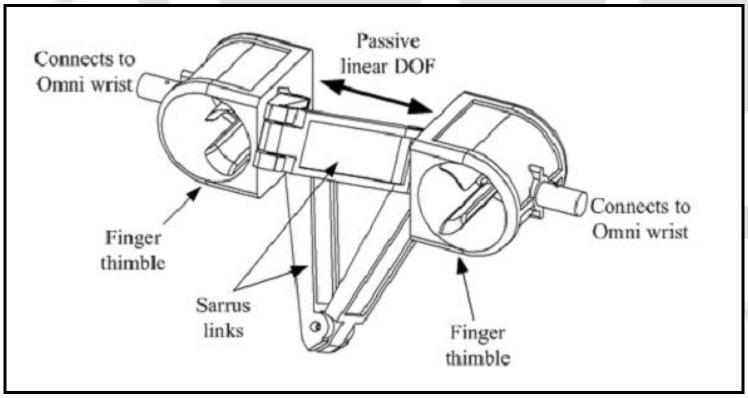


Figure 2.15: Gripper attachment (Ang et al., 2011).

Falcão and Soares have discussed physical prototyping and testing expensive and difficult to modify factors (Falcão & Soares, 2013) and suggested usability tests to be part of a design methodology. During usability testing the virtual prototype should be viewed, listened, and touched by all the actors involved in its design, including the

TH-1503_126105008

potential users, as if it was a real physical product. The use of Virtual reality technology has the potential to overcome such problems, allowing a better communication between designers and users.

Research gap identified: work was not supported by experiment.

Gao et al. have studied the perceptions due to body posture and hand gesture (Gao et al., 2012). Authors, while experimenting squeezing the virtual lady's hair clip with dual PHANToM interface and tooth brush (power grip) with single PHANToM (**Figure 2.16**) studied three styles of grip such as power grip, precision grip and Scissor grip. How the neck of the toothbrush deforms and how the toothbrush tip interacts with working environments, too soft or too stiff toothbrush necks was studied. Similarly, stiffness of hair clips also studied. The method used a point probe to touch the virtual object and found the participants felt the deformation and elasticity of the toothbrush.

Research gap identified: Authors focused on the stiffness/elasticity and didn't consider other parameters such as weight, surface texture, etc.

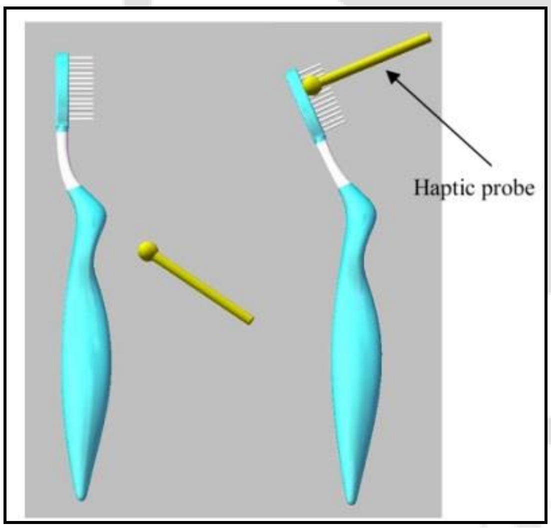


Figure 2.16: Testing the stiffness of toothbrush (Gao et al., 2012).

Ye et al. have mentioned the advantage and importance of virtual reality technology in substantially reducing the costs and the lead-time, and the ability for product evaluation throughout the various stages of a design process (Ye et al., 2007).

TH-1503_126105008

Also proved the efficiency and effectiveness of VR base technologies in comparisons with traditional techniques used during the product design evaluation process. This was investigated, through applying virtual reality technologies on: 3D haptic interaction and 3D stereoscopic viewing and integrating and implementing VR based technologies in to a Computer Aided Product evaluation application.

Research gap identified: Research only focused on mobile phone evaluation with the help of VR and stereoscopic LCD glasses; advantage of design in 3D space vs. 2D model display.

Seth et al. have developed low cost flexible architecture that can perform multi-body collision detection and simulate part behavior while performing virtual assembly of mechanical components in a virtual environment (Seth et al., 2005). This system is capable of importing CAD models, providing haptic feedback and stereo vision to the user for interacting with complex digital models present in the virtual scene. They have shown the potential benefits of virtual assembly in identifying issues related to assembly, early in the design process where changes can be made easily and inexpensively. Furthermore, they demonstrated successfully the ability to communicate multiple VR system at geographically dispersed location using a non-dedicated network channel. This may allow designer/engineers to conceptualize assembly sequences. In addition to this, authors highlighted the advantage of haptics in providing the touch feeling to differentiate soft from hard parts, light from heavy parts and smooth and rough surface and for virtual product assessment.

Research gap identified: Authors mainly focused on developing algorithm that helps multi-body collision detection and simulating to study part behavior during assembly. They didn't mention and studied user centric of the device.

Overall research direction:

This research mainly focused on two issues based on the research gap identified: primarily, studying the advantage of haptics in providing the feeling to users and differentiates soft from hard, light from heavy and smooth from rough surface, etc. and

TH-1503_126105008

secondly, usability study of PHANToM Omni™ (force feedback device) for all object parameters. The study also motivated due to the following reasons.

- Plastic products are widely used in a day to day life for different purpose such as water packaging, oil packaging, detergent packaging, etc.
- Report on plastics processing industry error fixing studies by Consulting engineers for plastics processing and plastic products (Tangram Technology Ltd., 1998).
- Research gaps was identified from different work related to usability evaluation of PHANToM Omni™.
- Needs to widen the use of haptic technology for use by the designers/engineers, and for academic purpose.

2.7. Usability

Usability testing is considered to be one of the most important, decisive and widely used methods in a competitive market to interact with the customers/users requirement. Usability is about the product's ease of use; these means the ability of a product or system to be used in an effective, efficient and enjoyable way by a specific population of users for intended purpose/objective within a given environment. This kind of activities can be applied during product design process or after getting the physical prototyped product and this was being practiced for long time. During this, it is a better approach and fruitful method to allow more experienced and valuable users/customers to participate and practice during product conceptual stage, and then allowing valuable customers to participate during design process makes perfect methods to advance the product design methods. In this research during the product development (plastic products such as water bottle and jar, mobile and tea leaf plucking machine), usability tests were performed in the prototyping phase that corresponds to process of construction, modification and testing of prototypes until the targeted product realized. This could be true through the VR-haptic integration since haptic allows users to interact and practicing the use of intended virtual product.

TH-1503_126105008

CHAPTER 3

3.0. Haptics, haptic devices and their application in different discipline

3.1 Haptics

Human explores and manipulates objects in a day to day activities through visually scanning the environment with eyes to locate the position of the object with respect to his/her location and touches the object to feel its shape; thereafter with a more careful manual exploration is made to investigate the surface and material characteristics of the object. Manually sensing of shape, softness, texture, rigidity, friction, stiffness of an object occurs through haptic sensory systems. Heller & Schiff in their books have explained in detail regarding the anatomy and physiology of the skin - characteristics of the skin (Heller & Schiff, 2013). In this part, it is attempt to highlight the location of the three layers - the epidermis, dermis and hypodermis of human skin which are responsible for our ability to feel the sense of touch, pressure, pain and temperature as it is seen in **Figure 3.1**. More focus on the touch sense is given because of its uniqueness unlike the other senses; touch (sensory receptors) is distributed over the entire body and focus area of the research. In addition to this, attempt is made to show the working principles of haptic devices and their applications. Haptic is a word that has been taken from Greek word "haptikos" meaning being able to come in to contact or touch that refers to the ability to perceive the environment through the sense of touch, and consist of the acquisition of both tactile and kinesthetic information and it is also called tactile-kinesthetic. A tactile and kinesthetic perception usually goes together; therefore, they are considered as one, namely haptic. Tactile perception is felt through pressure against or motion across the skin due to tactile receptors located over the entire body while kinesthetic refers to the information acquired by the sensors in the joints i.e. body movements, positions of joints and muscle feelings. In general together they provide information about object qualities, body movement and their interrelationships (El Saddik et al., 2011; Kadlecek, 2011; Salisbury, Conti, & Barbagli, 2004; Zilles, 1995).

TH-1503_126105008

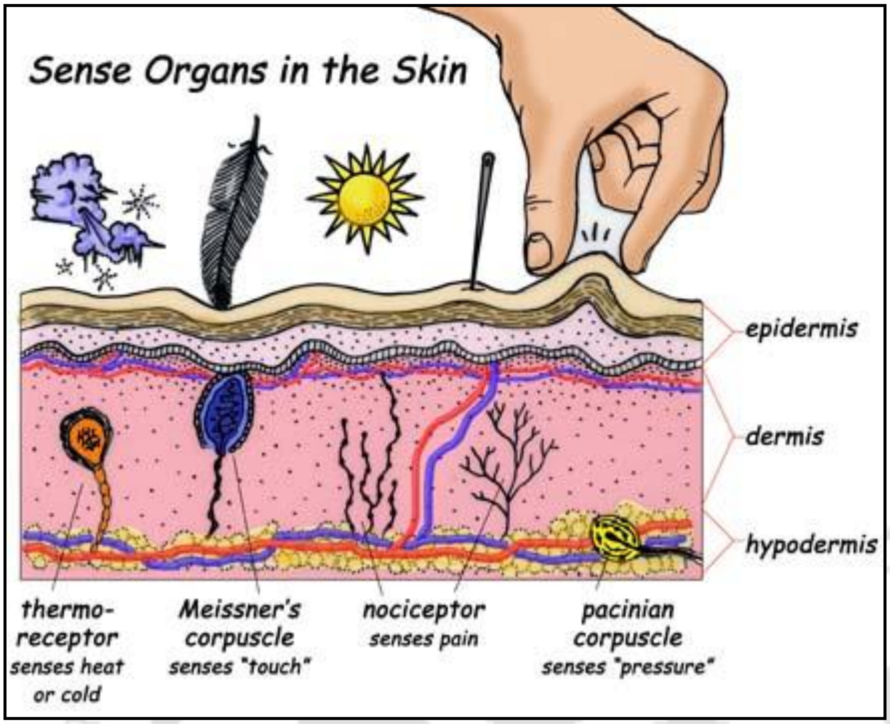


Figure 3.1: Touch sense (tactile sense) ("Haptic Feedback Technology," 2012)

To have a brief and thorough understanding of haptic senses, controls and feedback, it may be better to see the analogies of human haptics system to computer haptics system as shown in **Figure 3.2** (in this demonstrations some of the figure by MIT has been replaced/modified by the latest figure), which was used by MIT touch lab during their research that aims to understand the human sense of touch, and develop and enhance human-machine interaction in the virtual reality system. As it is shown, the left side part of the figure represent human senses of touch, involves a closed loop system of receptors, transmitting messages to brain and after processing messages transmitted from brain for manipulating and controls the position of the fingertip, and the right side of the figure, represents the haptic device exerted force to simulate contact with a virtual object in a similar way. In this system, the similarity of working principle of both systems sensors (nerves with encoders), processors (brain with computer), and actuators (muscles with motors); and the interaction between human and machine is shown.

TH-1503_126105008

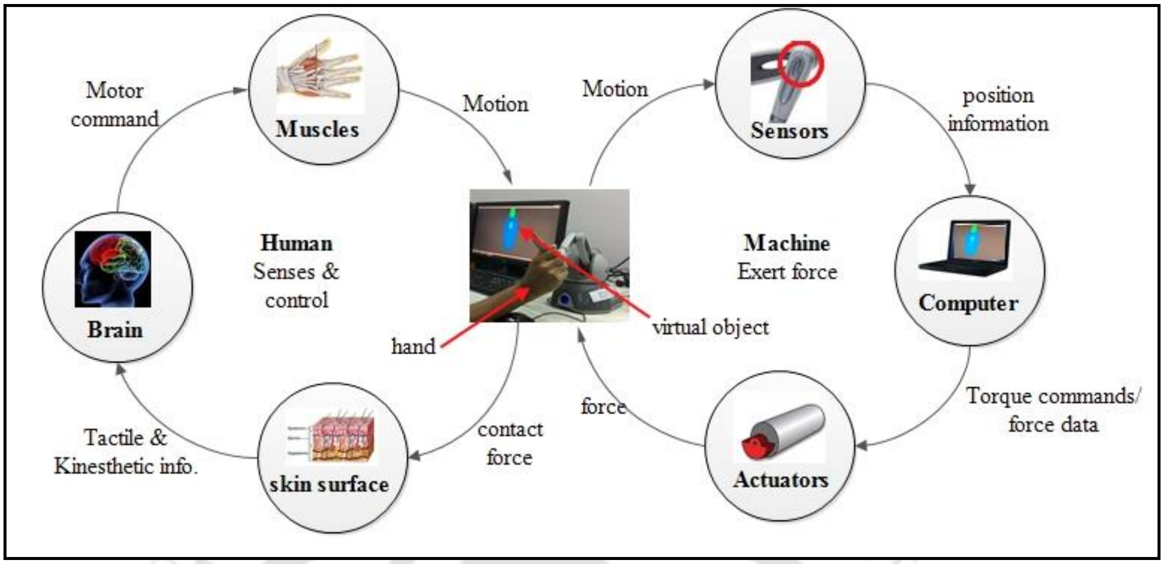


Figure 3.2: Human-Machine haptic interaction (Srinivasan & Basdogan, 1997).

Classification of haptics

As stated by various authors (El Saddik et al., 2011; Laycock & Day, 2007; Srinivasan, 1995), research in to Haptics feedback usually classified in to three areas: human haptics, machine haptics, and computer haptic. The terms are commonly used as it is explained below and it is also attempted to have clear idea of the relationships between VR/AR and haptics as depicted in **Figure 3.3**.

Human haptics: - is the study of human being's experience of touch perception and manipulation (human motor, touch and cognition, human sensory system and haptic anatomy).

Machine haptics: - is concerned with the design, construction, and use of robotic arms and hands to replace or augmented human touch and feel their environment (haptic control, robotic inheritance, sensing technology, and actuation technology).

Computer haptics: - is concerned with computer mediated i.e. algorithms and software associated with generating and rendering the touch and feel of virtual object (collision detection, haptic interface modeling, and physics based haptic simulation and collision response). Through haptic interaction system, operator can feel the force related properties from a virtual world including gravity force, inertia force, frictional force,

TH-1503_126105008

contact force and reaction force. Mainly, current work of this thesis research falls in this category.

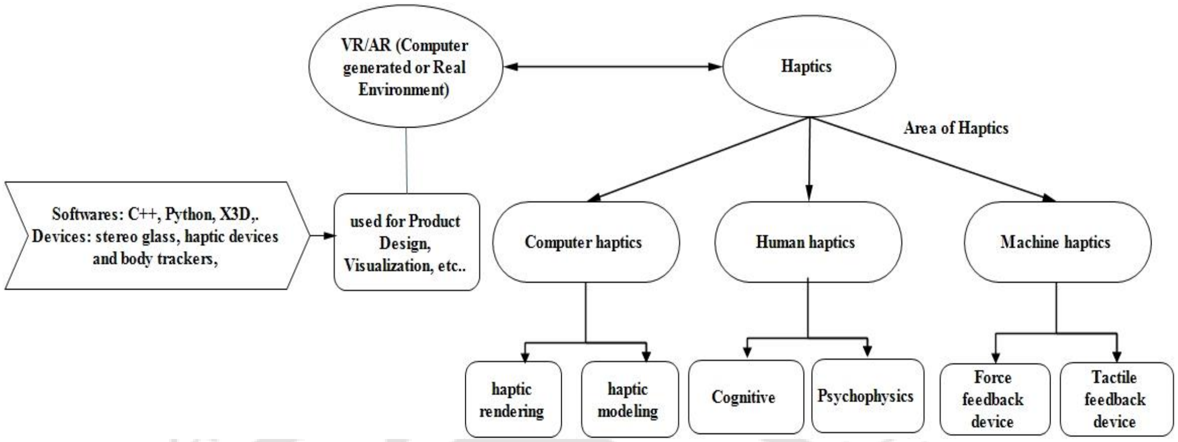


Figure 3.3: VR/AR and classification of haptics.

Source: Author generated based on reviewed literature

3.2 Interaction with virtual object using haptic feedback device

Through haptic devices, users can interact with a virtual model by feeding information to the computer and receiving information through force feedback (tactile vibration perceived). As a common practice, during the product design development, usability tests are usually performed after the physical prototype is available; now with the integration of VR, haptic model (virtual object) with the haptic feedback device during the product design development process it allows to test and evaluate the usability without incurring cost for prototyping (Gao et al., 2012; Pontonnier et al., 2014; Pungotra, 2012; Teklemariam & Das, 2015). A haptic device (PHANToM Omni™, phantom premium, delta, freedom, Omega, glove etc.) is equipped with a number of sensors, which record parameters like direction, position and velocity of the movement. As it is shown in **Figure 3.4**; the output/virtual object displayed from the computer, the computer performed calculations on haptic parameters, and transmitted this data to the haptic equipment for output to the user. These parameters are processed in an appropriate way and in effect, the user is receiving feedback (force), for example through tactile vibration at selected locations; force may be generated by a haptic interface when colliding with

TH-1503_126105008

the specified shapes and surface. This may allow users to feel the stiffness, weight and the object shape, edges, embossing and recessed features of the products. According to Salisbury & Srinivasan, (1997), to evoke the sensation of touching objects; the geometric modelling, material, kinematic and dynamic properties of the virtual object required to manipulate. Following this, it is also inevitable to select the appropriate rendering algorithm as a computational method to determine the forces that result when we interact with the virtual objects. Producing the sensation of touching on the selected object surface may exerted force to the user hand/fingertip which is proportional to the pushing depth of the phantom endpoint (generated stylus tip) on the surface.

Figure 3.4 may explain the three blocks (input/output characteristics of the user, haptic interface and virtual environment) and how a user can touch, feel and manipulate virtual objects

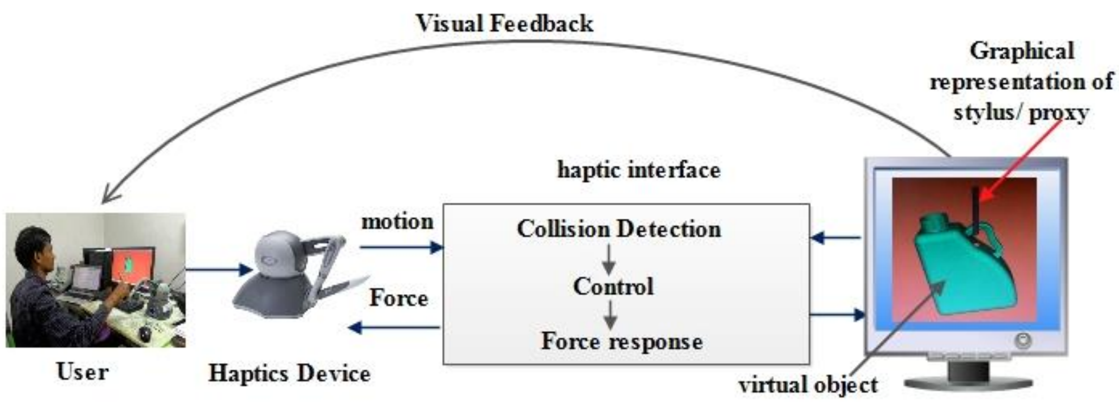


Figure 3.4: The process associated with haptics device-virtual object interaction

Source: Author generated based on reviewed literature and experimental setup

As stated by various authors (Cagatay Basdogan & Ho, 2002; Howard & Vance, 2007; Laycock & Day, 2007; Robles-De-La-Torre, 2008) and experimented, during the movement of the stylus (probe) the collision detection algorithm may check if the end point is in contact or is about to occur with the virtual object. The pushing depth is calculated as the distance between the current haptic interface point and a surface point. The response to the detection of collision in terms of how the force reacts against user during touches using the proxy on the surface is computed. During this, the interaction

TH-1503_126105008

between the simulated virtual object and the generic stylus of haptic device is represented by means of spring-damper system as it is shown in **Figure 3.5**, $F = Kx + C\dot{x}$, where K is the spring constant; x is displacement or depth of pushing; C is damping coefficient, and $\dot{x}$ is the velocity of haptic interfacing point. x= $(X - X^1)$, (proxy - probe). When the user touches the top surface of the object reference '*X'* is fixed at that point of touch and as the user press the surface it moves to 'X^1'. Here as it is shown in the equation the damper may provide reasonable accuracy and speed for real time interaction.

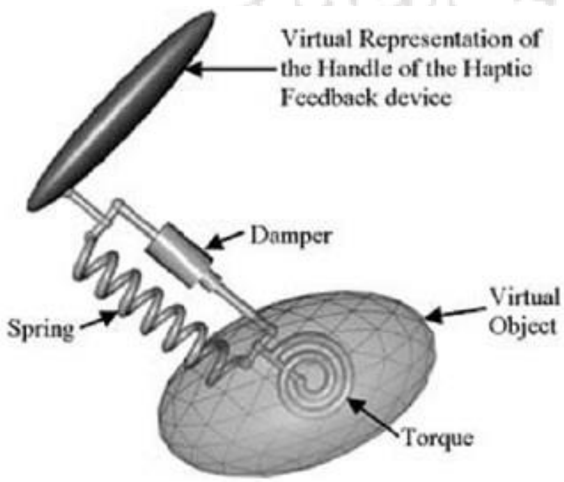


Figure 3.5: The linkage model of virtual object to the haptic feedback device stylus/handle (Laycock & Day, 2007).

In this research work, it has been practiced to identify and analyze the shape, stiffness, weight, surface texture of sample products using SensAble's PHANToM Omni™ haptic device; regarding PHANToM Omni™ detail information provided in section 3.3.2. This device has been used to sense through rubbing along the surface and poke on the different haptic models through the proxy/stylus to perceive the aforementioned characteristics (see **Figure 3.6**). When poking into the surface of haptic object, the perceiver experiences both geometrical and forces information through the stylus/proxy.

TH-1503_126105008

Figure 3.6: Rubbing and poking process with the proxy

Source: Author generated

3.2.1 Terminologies used and their full meaning and applications

Haptic device

Haptic device is one implemented to make it possible to establish physical contact between the computer and users. This device comprised of sensors, actuators, or both.

Haptic interface

Haptic interface consists of a haptic device and software based computer control mechanisms. It enables human-machine communication through the sense of touch. By using a haptic interface, someone can not only feed the information to the computer but can also receive information or feedback from the computer in the form of a physical sensation on some parts of the body.

Haptic perception

Haptic perception is the process of perceiving the characteristics of objects through touch. For example, perceived surface texture might be characterized in terms of roughness, friction, frictionless. The perceived roughness grade or size also determined through touch and drag fingers along/over the surface.

Haptic rendering

Haptic rendering is the process of determining the forces and torque based on the position and orientation of the haptics device. Haptic rendering is a system that consists of three parts; a collision detection algorithm, a collision response algorithm, and a control

TH-1503_126105008

algorithm (see **Figure 3.4**). Using haptic rendering users would be able to touch, feel, explore and manipulate the virtual objects (Basdogan et al., 2007; Laycock & Day, 2007; Yadav & Krishnaiah, 2013). This may enhance the user experience in virtual environment. It involves sampling the position sensors at the haptic device (servo cycles of the haptic device) to obtain the user's position within the virtual environment. Basdogan et al., (2007) "*As a user manipulates the probe of the haptic device, the new position response and orientation of the haptic probe are acquired and collisions with the virtual objects are detected. If a collision is detected, the interaction forces are computed using programmed rules for collision response, and conveyed to the user through the haptic device to provide users with the tactual representation of 3D objects and their surface details*".

In general detection collision occurs in three consecutive stages as follows: collision detection between the simulated stylus and the bounding box of the virtual object; collision detection between the simulated stylus and the bounding box of each triangular element; and collision detection between the simulated stylus the triangular element itself. Existing Haptic rendering algorithms were described as shown below in addition to partially listed parts of the code belong to rendering (Arroyave et al., 2014).

To obtain the present position of the end effector is by means of function:

hdGet Doublev (HD_CURRENT_POSITION, POS); similarly, to get the orientation of the joints of the haptic device, as well as of the wrist's joints; hd GetDoublev (HD_CURRENT_JOINT_ANGLES, JAn);

hd GetDoublev (HD_CURRENT_GIMBAL_ANGLES, gAn); Then, the force is sent to the haptic device by, hd SetDoublev (HD_CURRENT_FORCE_F+Fd);

3.2.2 Haptic rendering algorithms

Since the inception of this technology till date different types of rendering algorithms were implemented to render 3D objects, the 3D object can be either surface based or volume based for the purpose of computer haptics. In this part it is attempted to list out and highlight the existing rendering algorithms as follows:

TH-1503_126105008

The first rendering algorithm god-object algorithm introduced by Zilles & Salisbury, (1995) which is a point proxy based to render polyhedral representation of objects. It means the haptic device position followed by the virtual representation of haptic device which is called proxy. The term god-object was used by Dworkin & Zeltzer, (1993). It is also adopted in a similar sprit by Zilles & Salisbury, (1995) to describe a virtual object controlled by a human user in physical simulation.

The second rendering algorithm Ruspini algorithm introduced by Ruspini, Kolarov, & Khatib, (1997), which is a sphere proxy based and the enhanced version of God object algorithm, Ruspini algorithms allows to change the size of the sphere as it is required,

The third rendering algorithm Chai3D which is a force rendering algorithm has been developed by a team at Stanford university in California, which used Chai3D rendering library and,

The fourth rendering algorithm OpenHaptics has been developed by SensAble technology, which used OpenHaptics rendering library (this algorithm is device specific for SensAble devices).

In this research Ruspini algorithm and OpenHaptics rendering library has been used during the experiment and it was observed that, these techniques are better than god-object algorithms in reducing fallthrough problems even though not nullifying the problem.

3.3 Hardware and Software

Primarily it was important to study what software, hardware and procedures are required to conduct experiment and collect data by allowing participants to perform on it, and for proving or disproving the hypothesis. To do so, haptic interface devices and associated computer hardware and software were used during pilot and final experiment to understand haptic perception of shape, surface texture, stiffness, and weight. In addition to this, it was also taken in to account to be in line with the recommendation/ others research outcomes (R.-J. Chen, Lin, Chang, Wu & Lee, 2011; Kadlecek, 2011; Novint Technologies Incorporated, 2008; Robles-De-La-Torre, 2006, 2008) that the program must ensure the refreshment rate for human vision at least 30 times per second (for

TH-1503_126105008

collision detection and remodeling process), to remain within the limitation of human vision and for smooth haptic sensation without discontinuity (for displacement observation and force estimation) human needs approximately 500 times per second to 1000 times per second or higher frequency vibration. Under this part it is also attempted to brief in subsection 3.3.1 regarding software and in subsection 3.3.2 hardware used in the entire research work.

3.3.1 Software

In this research, different open source and commercial software development toolkits have been employed to conduct the experiments. Software is required to integrate various hardware devices into a coherent system that enables the user to interact with the virtual environment. Mainly it has used CATIA modeling software for product design, OpenHaptics^{TM} SDK toolkit from SensAble, and H3D open source software from H3D.org. OpenHaptics toolkit includes the phantom device driver (PDD), the haptic device API (HDAPI), the haptic library API (HLAPI), utilities and sample codes. OpenHaptics toolkit allows both lower and higher level programming access to the PHANToM; with in this API there are two implementations for reading the current position of the haptic interface and rendering feedback forces-haptic device API (HDAPI) and haptic library API (HLAPI). But this API doesn't have scene graph (the source is closed), due to this the latest H3DAPI 2.3.0 version was used for this research purpose; as described in (H3D.org, 2008) H3D is the term used to refer the entire package of H3DAPI, HAPI, H3DUI, MedX3D, H3DUtil and H3D physics. H3D is a scene graph API that performs both graphic and haptic rendering from a single scene description. H3D allows users to access and manipulation of haptics device properties in the X3D and python (a high level scripting language) via H3DHapticsDevice node. It may be important to discuss in depth to have better understanding of H3DAPI, HAPI, X3D and other programming language.

H3DAPI

H3DAPI is a completely open source haptics software development platform that uses the open standards OpenGL and X3D with haptics in one unified Scene graph to handle both

TH-1503_126105008

graphics and haptics. H3DAPI is cross platform and haptic independent; it enables haptic programmers to render forces directly, offers direct control over configuring the runtime behavior of the drivers and provides convenient utility features and debugging. Furthermore, it is excellent tool for writing haptic-visual applications that combine the sense of touch and 3D graphics using C++. This can be done with H3DLoad project file or Makefile and this will make them available when running H3DLoad. H3DAPI has a bunch of nodes like device handling, Dynamic Transform, coordinate, deformable shape, etc. As the work focused more on deformation, surface and shape evaluation it may be better to highlight some of the parameters about deformable shape; It is an X3DShape node which makes it possible to deform the geometry of the shape when touching it with a haptics device. The deformer field specifies an H3D Coordinate Deformer node that determines how the coordinates should be deformed during contact. In this node i.e. Deformable Shape has three fields which are related to the description of plasticity: ***origCoord*** which contains the coordinates of the geometry before deformation specified by the coordinates of Deformable Shape's geometry, ***restingCoord*** which contains the final coordinates of the geometry after deformation and ***deformedCoord*** which are the coordinates of the geometry as the deformation occurs. A non-plastic deformation would ensure that the values of restingcoord are always the same as that of origcoord, while in a full plastic deformation restingcoord is always the same as ***deformedCoord***. The extent to which the ***restingCoord*** falls back to the ***origCoord*** is adjusted with ***plasticity*** value between 0 and 1.

OrigCoord=RestingCoord; non-plastic deformation

RestingCoord=deformedCoord; plastic deformation

HAPI

HAPI is a fully modular haptic rendering engine that allows users to add applications from the scratch, substitute or modify any component of the rendering process. HAPI consisted of the following parts: ***device handling*** (device handling layer may provide independent interface for various haptics devices such as PHANToM devices from SensAble Technologies, Delta and Omega devices from ForceDimension, Falcon from Novint and HapticMaster from Moog FCS Robotics); ***Geometry based haptics*** such as

TH-1503_126105008

collision handling algorithm, *haptics rendering algorithm* (this is important to calculate the force and torque from the interaction of the haptics device with the objects in the scene), and *surface interaction algorithm*; ***free space haptics*** (force effect that depends on the state of the device position and orientation without touching geometries such as gravity, springs, etc..) and *thread handling* (this may use to calculate forces generated from all force effect and geometries that are rendered on a haptic device), **Figure 3.7** shown below may delineate .

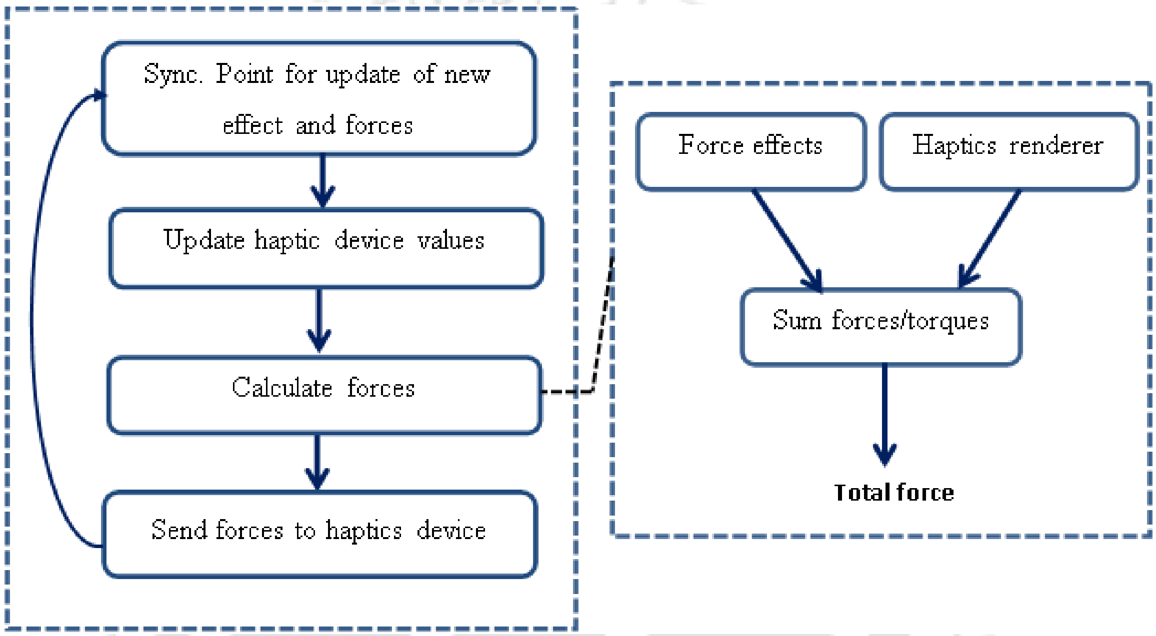


Figure 3.7: The flow of execution in the haptic thread (SenseGraphics, 2014)

Programming

During the experiment, codes has been developed in two steps to create the sense of touch for a virtual object. First, the haptic device to be used was specified and second, a set of haptic properties has been defined for each touchable object. To specify the haptic device an instance of the device information node was created and the haptic device is added to it. HLHaptics device is the node used to manipulate a Phantom device. To display and manipulate the X3D files with haptic feature H3D viewer was used. In addition to this H3DLoad setting were used to configure and customized the haptic device type to take any device (H3DAPI setting folders).

TH-1503_126105008

X3D

X3D is a new extensible 3D file format based on XML and is used by H3D as an easy way to define geometry and arrange scene-graph elements such as a user interface. H3D has a full XML enabled X3D parser and automatically supports predefined X3D nodes as well as any new nodes developed for different application toolkit. X3D used in avoiding long lines of unmanageable C++ scene-graph descriptions that are hard to read, maintain and debug. X3D is comprised of nodes and fields which represent a structural division. Fields are data containers that store and manipulate properties; and nodes are a container that group related fields together to define objects in the scene (Granados, 2008; H3D.org, 2008). Some of the X3D nodes are listed and attempted to explain in brief: to list few of the nodes such as Group, Shape, Appearance, color, coordinate, indexedFaceset, indexedTriangleSet, Material, Transform, etc. To highlight the difference between indexedFaceset and indexedTriangleSet; indexedFaceset is a 3D shape formed by polygon faces between vertices and indexedTriangleSet is a 3D shape formed by triangles between vertices. Each node in the graph is an instance of one of the available node types. To give detail information regarding those nodes mentioned above it has been tried to express as shown below; shape node defines a shape, a transform node positions, orientation and scale its children nodes, etc...

<Transform position= ' ' orientation= ' ' Scale= ' ' />

This node is the most important node to control the position, orientation and scale of its children.

<DeformableShape>

This node has two and above fields such as appearance, Geometry, etc…

<Appearance>

The appearance node defines the look of the geometry. This node can only be defined inside a Shape node. The fields included in this node are: material, texture, etc... All fields are optional but at least one field should be specified.

<FrictionalSurface stiffness= '1' damping= '0' staticFriction= '0.8' dynamicFriction= '0.2'/>

TH-1503_126105008

The surface nodes are H3D-specific nodes. There are four surfaces currently implemented in H3D, these are SmoothSurface, FrictionalSurface, MagneticSurface and DepthMapSurface.

<Material DEF= 'material_0' diffuseColor= '1 1 0.6'/>

The material field contains a material node. This node specifies the color of the associated geometry. This node has six fields such as diffuse Color, emissive Color, ambient Intensity, shininess, specular Color, and transparency.

</Appearance>

<IndexedFaceSet solid= 'false' coordIndex= '47 ….-1'>

The indexedFace set node represents a 3D shape formed by constructing faces (polygons) from vertices listed in the coordinate field. The coordinate field contains a coordinate node that defines the 3D vertices referenced by the coordIndex field. An index of "-1" indicates that the current face has ended and the next one begins.

<Coordinate point= '-19.4 2.9….-5.2'/>

In this field coordinate point shows how they join, the first point in the coordinate list to the second point, and then join the second to the third, etc., and finally the final to the first to close the region which defines the shape.

<Normal vector='-0.1…'>
</IndexedFaceSet>
<IndexedFaceSet USE='IND1' containerField="hapticGeometry"/>
</DeformableShape>

In addition to this, it is also important to highlight the dynamic transformation nodes that used to define properties of rigid body motion, since it was used in perception of tea leaf plucking machine virtual model weight experiment.

<DynamicTransform DEF='Tealeafp'>
Mass='3.5'
<Shape>
<Appearance>
<Material DEF='_material0' diffuseColor='1 1 0.6'/ >
<FrictionalSurface dynamicfriction='' staticfriction='' />
</Appearance>
< Geometrical information with the dimensions >

TH-1503_126105008

```xml
        </Shape>
      </DynamicTransform>
```

During modeling, the virtual product may have different component and this components behavior and characteristics can be organized in an X3D through node <Group>. Group may collect related nodes together and this also allows reusing by defining the group parameters to the next component. In addition to this, it is also shown how the device/stylus information and rendering algorithms define in X3D.

```xml
<DeviceInfo>
    <PhantomDeviceName="PhantomOmni" >
<RuspiniRenderer DEF="renderer" proxyRadius="0.05"/>
    <Shape containerField="stylus" >
          <Appearance>
            <Material diffuseColor="0 0 1"/>
          </Appearance>
          <Sphere radius = "0.05" />
    </Shape>
  </PhantomDevice>
</DeviceInfo>
```

Haptic scene graph

It is a combination of nodes that gives meaning of action; hierarchy of graphical nodes as children and parents along with their haptic properties as shown in **Figure 3.8**. A scene graph haptic API often uses a tree structure of objects in the virtual world with a specific root node such as a world node. It is possible to apply graphical and haptical properties to an object and set the specific property to loop/recursively to its children objects.

TH-1503_126105008

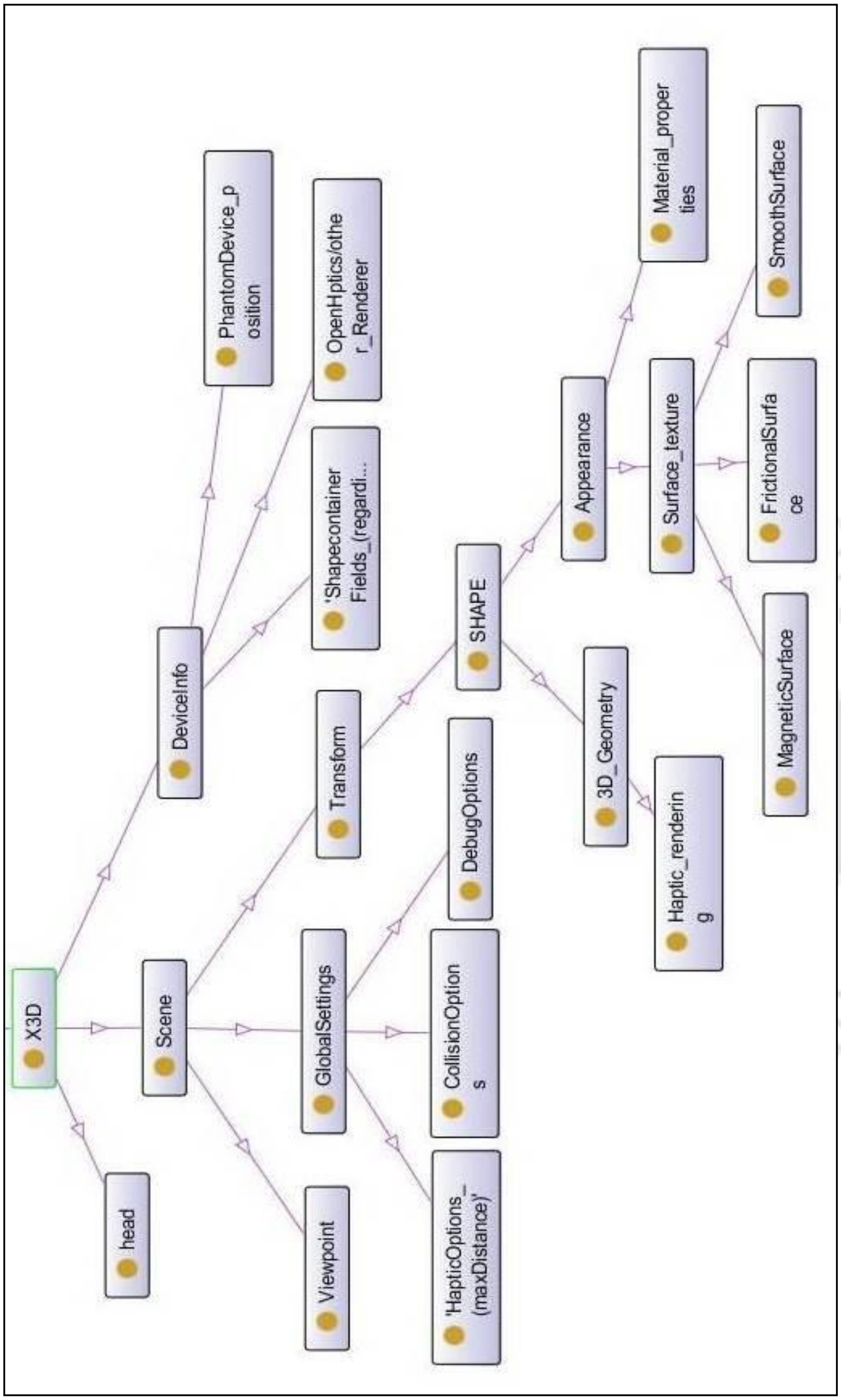


Figure 3.8: Hierarchical representation of X3D

Source: Author generated based on the H3D; X3D node class reference

Python

Python is a general purpose high level language with syntax, allows programmers to express concepts in fewer lines of code comparing to C++ and Java. It is also called an interpreted language, meaning that doesn't need to compile python scripts to run them. Therefore, this may help avoiding the compile phase of the compile-test-debug cycle, which allows rapid prototyping of application functionality. Here in general, python used to import global namespace, define special fields, setup routes, haptic device information, and make calculations that may not be handled by X3D and a lot more. This may work by adding a python script node to the scene-graph to obtain the python code to execute. Some of the syntax that calls libraries and others are shown below.

```
from H3D import*
from H3DInterface import *
# To get the current active device and to manipulate, it needs to import the definition which is listed below. But it is also important to make sure the proxy is drawn at the position of the haptics device.
<IMPORT inlineDEF="H3D_EXPORTS" exportedDEF="HDEV" AS="HDEV" />
di = getActiveDeviceInfo()
if( di ):
devices = di.device.getValue()
 for d in devices:
d.proxyWeighting.setValue( 0 )
```

As it is shown in the first line code, files included that are needed for setting up the scene graph are imported such as the following;

```
#include < H3D/X3D.h>
#include < H3D/Scene.h>
#include < H3D/MouseSensor.h>
#include < H3D/Material.h>
#include < H3D/X3DGeometry.h>
```


TH-1503_126105008

In this research, it was also used Python script to scales the coordinate to change the dimension ‘mm’ to ‘m’ scale the imported 3D object to fit in to the viewing box, during this the code listed below was used.

```
from H3DInterface import *
input_nodes = references.getValue() # I assume that all nodes given as references are Coo
rdinate nodes.
for n in input_nodes:
  points = n.point.getValue()
  new_points = []
  for p in points:
    new_points.append( p * 0.001 ) #mm to m
  n.point.setValue( new_points )
```

3.3.2 Hardware

There are different types of force feedback device with different performance and specification from different companies such as Omega, phantom premium, Falcon (Novient), delta, freedom, etc. as listed in **Table 3.1**.and shown in **Figure 3.10, Figure 3.11, Figure 3.12, Figure 3.13** and **Figure 3.14** but in this research PHANToM Omni™ of 3D system corporation has been used. The PHANToM Omni™ depicted in **Figure 3.9**, is a Force feedback haptic devices from Geomagic (formerly SensAble Technologies), can accurately measure the 3D spatial position (along the x, y and z axes) and the orientation (pitch, roll and yaw) of the handheld stylus. The device use motors to create the forces that push back on the user’s hand to simulate touch and interaction with virtual objects. In addition to this the position of user’s fingertip or hand monitors through the digital optical encoder mounted on the motors while measurement of rotations about these axes (roll, pitch and yaw) is done using potentiometers. This arm of the device could rotate in six directions, due to the design of the arms the angle of rotation and arm movement range were restricted to approximately 6.4 W×4.8 H×2.8 D inches. The maximum force that can be exerted at nominal position is about 0.75lbf or 3.3 N, while the device is able to exert a force of 0.75lbf or 0.88 N continuously for 24 hours (3D Systems Corporation, 2013). The direction of applied force on the virtual

TH-1503_126105008

object by the user, feedback force in to the user, rotation direction on each links and joints are also shown on **Figure 3.9**. PHANToM Omni™ force feedback device has been put to practical use for wide range of purpose. To list few of them, for medical training simulating purpose (Gosselin et al., 2013), product evaluation (Chen, Yang, & Lian, 2005; Falcão & Soares, 2013; Gao et al., 2012), as a virtual robot arm to interact with virtual prototypes in a virtual assembly environment by providing kinematic and dynamic models, and defining the properties (Chen, Ong, Nee, & Zhou, 2010).

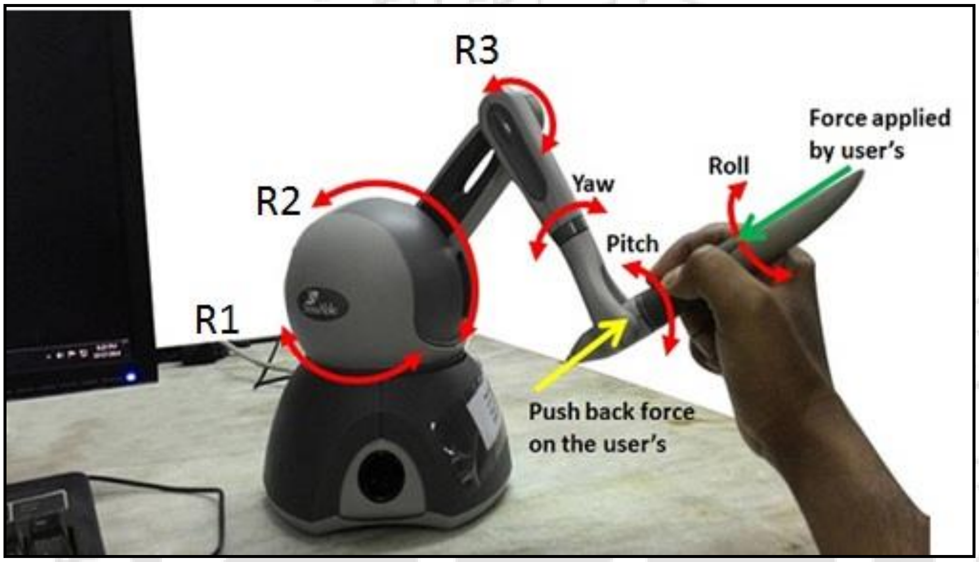


Figure 3.9: PHANToM Omni™ force feedback device rotation and applied force directions

Table 3.1: Comparison of performance specification between different types of haptic device

Product Name	DoF	Peak force	Continuous force	stiffness	workspace	structure
Omni (Sensable)	6//3	3.3N	0.9N	2.0 N/mm	120mm	Serial
Phantom 1.5	6//3	8.5N	1.4N	3.5N/mm	267mm	Serial
Freedom cubic	7	2.5N	0.6 N		290mm	Serial
Omega.x (Force dimension)	3	N/A	12N	14.5N/mm	110mm	Parallel
Falcon (Novint)	3	N/A	9 N	8N/mm	100mm	Parallel

TH-1503_126105008

Figure 3.10: Omega.6 haptic device ("Omega Haptic Device," 2005)

Figure 3.11: Phantom premium haptic device (3D Systems Corporation, 2013)

Figure 3.12: Falcon haptic device with ball and pen type manipulator ("Novint Falcon," 2007)

Figure 3.13: Delta haptic device (Iman Brouwer, 2012)

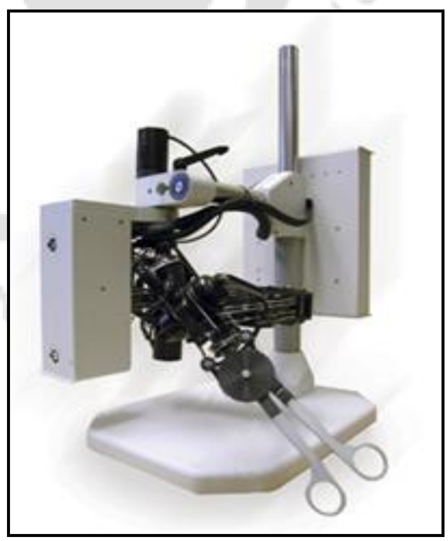


Figure 3.14: Freedom haptic device (Iman Brouwer, 2012)

TH-1503_126105008

3.4 Application of haptic feedback device and VR in Design education

There are certain problems of VR systems which are not integrated with haptic feedback devices. These problems include lack of depth perception, lack of perception of tactual properties etc. of the virtual prototype while designing in a virtual environment. Due to this fact designers/ design students may not able to develop appropriate product prototype for rapid prototyping. Therefore, repeated rapid prototyping is required for taking decision about ultimate product that will be manufactured further. Thus, this ultimately leads to increase in cost of rapid prototyping as more rapid prototype need to be developed for taking ultimate product decision.

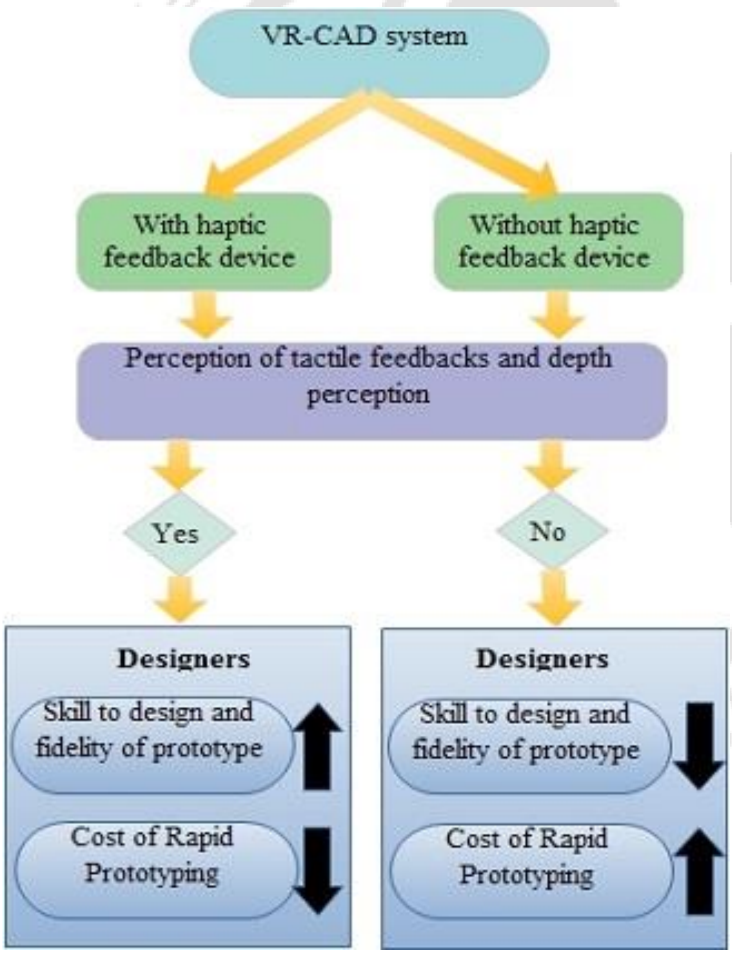


Figure 3.15: Flowchart showing the impact of VR with and without haptic on Prototyping;
Source: Author generated

TH-1503_126105008

In **Figure 3.15,** it was depicted how designer may rely on the integrated VR-Haptic system to gain the skills of virtual prototype development and fidelity of the prototype. **Figure 3.15** is also able to express the importance of tactile feedback and depth perception during prototype development. Actually, haptic feedback system enhances virtual prototype fidelity which ultimately leads to less number of rapid prototyping as well as cost reduction for rapid prototyping. With the present conceptualized frame work, it is clear that this kind of system may have some impact on design process.

Therefore, design faculty may use this kind of system to teach prototype development to their design students for better design outcome. For instance, usability of the virtual model of tea leaf plucking device (**Figure 3.16**) has been evaluated with VR-Haptic feedback system such as "PHANToM Omni™ Haptic" which enabled the tactual feedback as well as depth perception. In this evaluation process it is assumed that VR-Haptic integration will be helpful tool to reduce cost of prototyping, and time to market. In general, combined VR and haptics have the potential to facilitate and bring to the best level of the understanding of various phenomena as well as to promote new methods for design education.

Figure 3.16: Battery operated Tea leaf plucking virtual model

Source: Author generated

TH-1503_126105008

CHAPTER 4

4.0. Experimental setup, data collection and analysis

The experimental setup and procedure of the experiment are described below. The setup consists of the following components:

I. Perceiver/users,
II. Haptic device (PHANToM Omni™),
III. Virtual object in a CAD Environment, and
IV. The haptic interface.

Data analysis and result interpretations were conducted after data collection through post-task questionnaires which has been given by 84 participants.

4.1 Experimental setup

Installation of IEEE 1394 FireWire card in to the PC, interfacing the haptic feedback device (PHANToM Omni™) with the PC, and installation of Phantom Device Drivers (PDD) to control the communication of the device with the computer. H3DAP from h3d.org was installed that gives the platform to write different code. Thereafter, different virtual objects using CATIA V5 R19 were prepared and converted to X3D format files. Finally, codes have been generated for scene nodes, fields and choosing haptic renderer, which was used to added haptic feedback in to the virtual objects.

4.2 Data collection

4.2.1 Questionnaires preparation

Questionnaires were prepared with 5-point Likert scale and open-ended questions focused on the usability of haptic feedback system, the virtual object evaluation and general information of the respondents' (demographic profile, educational qualification and their exposure to haptic device). Thereafter, pilot data collection has been conducted with fifteen students to evaluate the strength of the questionnaires (reduce ambiguity and to standardize) and the feeling of designers and engineers towards the interaction of haptic device with the virtual objects. From this pilot data collection positive feedback

TH-1503_126105008

has been found and based on the feedback obtained, experiments and questioners were modified and preceded to final data collection. Full questionnaire is in appendix A and B.

4.2.2 Participants

A total of 84 students (whose details are given later) were approached and requested to participate and respond on the questionnaires, by allowing them to interact with the virtual object (simulating object hardness, geometric shape of 3D, surface smoothness and roughness, weight, etc.), which is displayed on a computer screen through the PHANToM Omni™ haptic device which renders the force feedback. Each participant spent fifteen to twenty minutes time for evaluating the virtual prototype properties as well as the usability of PHANToM Omni™ haptic feedback device itself. Two samples on each experiment have been employed such as carpet, water bottle, oil bottle, mobile phones, pen-holder, water jar and tea leaf plucking machine models. The experiment setup consisted of desktop computer interfaced with PHANToM Omni™ and Laptop were used for displaying the online questionnaires (created on Google drive) and to be filed by respondents'. The participants were from Department of Design and Department of Mechanical Engineering of IIT Guwahati, and participants were selected purposefully.

4.3 3D Haptic Shape

In this experiment, two-dimensional objects (Plate/Carpet adding static and dynamic frictions, and stiffness properties/scales, color and orientation to the surface) and 3D objects (different Bottles, water jar, pen holders, tea leaf plucking adding stiffness and gravitational force properties/scales, color and orientation) were implemented.

Procedure of the Experiment

Participants individually and in a group of three to four were invited and written document distributed which gives guidance how to proceed (some of the instruction listed below) followed by a demonstration. Thereafter asked to be seated individually and asked to grasp the haptics feedback device (PHANToM Omni™) stylus and perform by moving the stylus to all direction and pocking on the surface of water bottle, and carpet to perceive the stiffness (**Figure 4.1 and Figure 4.2**) and rubbing on the surface to perceive the surface texture of carpet and mobile phone (**Figure 4.2** and **Figure 4.3**) and perceive

TH-1503_126105008

the shape of the oil bottle, water jar and mobile phone (**Figure 4.3** and **Figure 4.4**), and hobbling to perceive the tea leaf plucking machine model as shown on the **Figure 4.5**.

Instructions to subjects, participating in the experimental work

1. Run the haptic feedback device (PHANToM Omni™)
2. Open H3D Viewer
3. Open the folder & select the program
4. Drag and drop the program to H3D viewer
5. Perform on the Haptic surface by rubbing, hobbling and poking through the stylus of the PHANToM Omni™, then
   - Perceive the surface roughness/smoothness and rigidity/stiffness of the two carpet,
   - Perceive the stiffness of two water bottles when poked,
   - Perceive the 3D shape of oil bottle and jar,
   - Perceive the shape and texture of the mobile phones,
   - Perceived the weight of tea leaf plucking by lifting through the stylus.

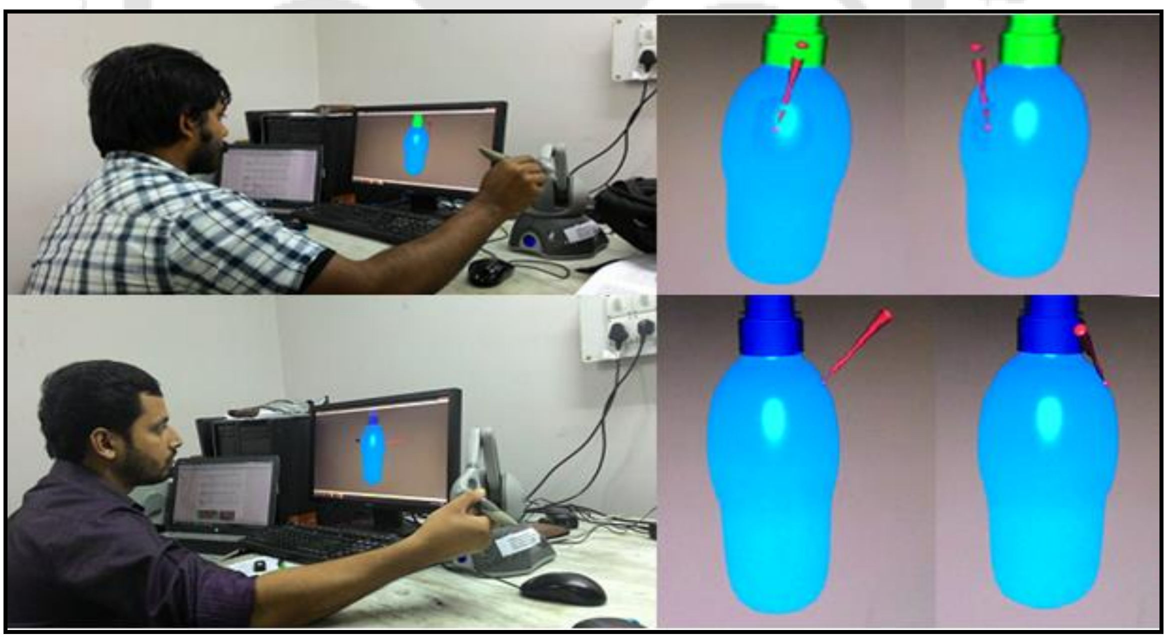


Figure 4.1: Perceiving stiffness of the bottle

TH-1503_126105008

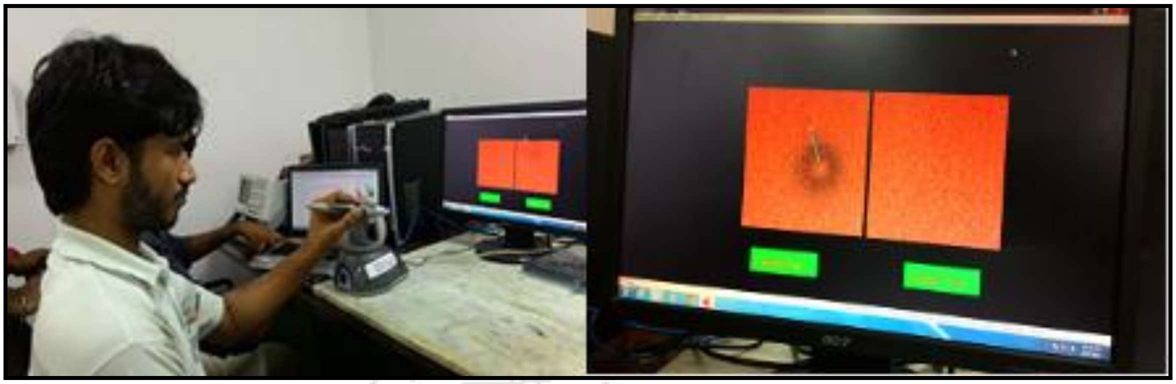


Figure 4.2: Perceiving rigidity and surface texture of carpet

Figure 4.3: Perceiving rigidity, shape and surface texture of mobile phone model

Figure 4.4: Perceiving 3D shape of the bottle & jar

TH-1503_126105008

Figure 4.5: Perceiving weight of tea leaf plucking machine

4.4 Data analysis and results

To analyze the results of the experimental data, it was initiated by identifying the type of variables (independent and dependent variables), number of variables and number of samples with appropriate steps to be used during data analysis.

Detail procedures

Prior to the data analysis, the objective of the experiment was defined, in order to segregate the results based on type that belong to the product evaluation or to the system usability as follows.

Objective of the research

1. Virtual object properties evaluation of such as (surface texture, stiffness, 3D form, weight).
2. Usability evaluation of haptic feedback device by the user (subjective and objective questioners).

Procedure followed to analyze the statistical data

1. checking the normal distribution of data or sample characteristics Shapiro-Wilk test *P*-value test, and visually inspection the histograms, normal Q-Q plots were used.
2. Reliability of the scale were checked using Cronbach's alpha and chi-square.
3. Description statistics (Mean, SD, Frequency, percentile, etc.).
4. Inferential statistics ANOVA followed by *F*-Test, *t*-test, *Z*-test, etc. were used.

TH-1503_126105008

1. Classified items related to objective 1

<u>Dependent variable</u>

System usability related questions (10 items)

Perception of surface roughness (1 item)
Perception of weight (1 item)
Perception of stiffness (1 item)
Perception of 3D Shape (1 item)

1. for reliability testing Cronbach's alpha, chi-square
2. one sample t-test (inference)

<u>Extraneous variables which are common for all experiments</u>

- Previous experience related to haptics device (percentile/frequency)
- Educational qualification (percentile/frequency)
- Age (Mean + SD)
- Gender (percentile/frequency)
- Types of 3D modeling CAD software used before (percentile/frequency)
- Cost related (Mean + SD)

2. Classified items related to objective 2

<u>Dependent variable</u>

Questioner related to perception of stiffness, roughness, 3D form/shape and weight of different virtual objects.

- Number of item is one (01) each.

<u>Independent variable</u>

- Numbers of products are two (02) each.

Cronbach's alpha, Pearson chi-square were used for reliability testing. Similarly, repeated measures ANOVA followed by *F*-Test, *Z*-test were used for inferential statistics.

4.4.1 Descriptive statistics of the respondents' demographical profile

Among eighty-four subjects' 16 were females (19%) and 68 were males (81%) (**Figure 4.7**), with in the age range of twenty to forty-five (Age 20-30 were 79.8% and Age above 30 were 20.2% of the total participant, detail shown in **Figure 4.6**.

TH-1503_126105008

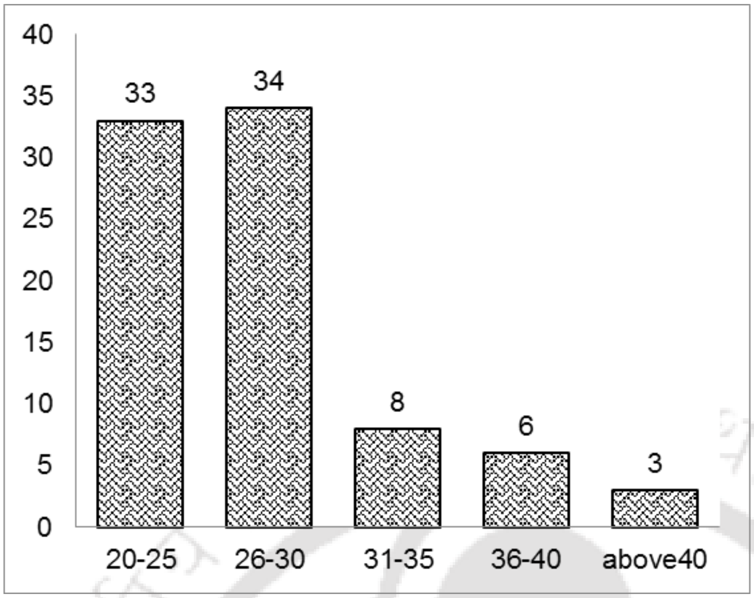


Figure 4.6: Distribution of participants by Age-group

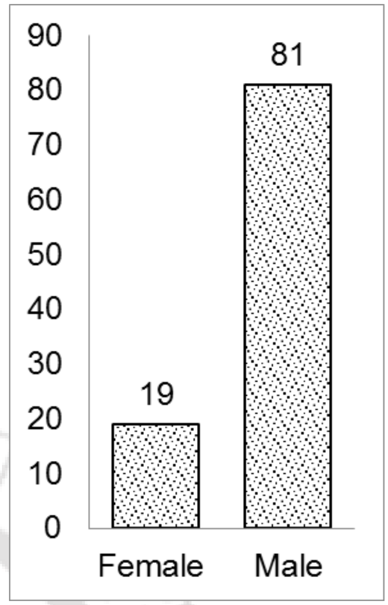


Figure 4.7: Percentile of participants by gender

4.4.2 Participant's haptic feedback device, 3D Software knowledge and their Educational qualification

As depicted in **Table 4.1**, participant with different back ground have been participated in these experiments, Participants with current enrollment from B.Tech. & B.Des. were 9 participants (10.7%), from M.Tech. & M.Des. were 39 participants (46.4%), PhD from both departments were 35 participants (41.7%) and one postdoc (1.2%) from Department of Design; Most of the participants were familiar with 3D modeling software but 13 (15.5%) of participants were not familiar with 3D modeling software, however, they are regular computer users. In addition to this they were asked about their exposure towards haptic feedback device; 78 (92.9%) of participants were novice and 6 (7.1%) participants were familiar to this kind of system.

TH-1503_126105008

Table 4.1: Demography profile, Educational qualification and 3D Modeling knowledge of respondents' in number and Percentile.

Age [N (%)]		**Gender [N (%)]**		**Current Academics enrollment [N (%)]**		**3D Modeling software [N (%)]**	**Haptic feedback device [N (%)]**	**Value for Money [N (%)]**
20-25	33 (39.3%)	Female	16 (19%)	B. Tech/ B. Des	9 (10.7%)	Novice 13 (15.5%)	Novice 78 (92.9%)	Agree with current price 44 (52.4%)
26-30	34 (40.5%)	Male	68 (81%)	M. Tech/ M. Des	39 (46.4%)	Worked with 71 (84.5%)	Worked or knew before 6 (7.1%)	Disagree with current price 40 (47.6%)
31-35	8 (9.5%)			PhD	35 (41.7%)			
36-40	6 (7.1%)			Postdoc	1 (1.2%)			
Above 40	3 (3.6%)							

4.4.3 Statistical Results of overall system usability - subjective measurement (haptic feedback device)

After checking normal or Gaussian distribution using Shapiro-Wilk test and Q-Q Plots, proceeded to reliability testing for scale on system usability. In system usability analysis, items are divided in two factors which termed as system usability in facilitating designers/engineers tasks (easiness to perform and to understand, reachability, comfortably, helpfulness, productivity) and system usability in perceiving surface texture, stiffness, weight, depth, and 3D form.

Results related to overall system usability evaluation

The following subjective questionnaire and results were aimed to show the importance of the system towards designer/engineers, product development facilitating, perception through point contact, etc.… questionnaires and hypothesis related to system usability are shown below. The 5-point Likert scale evaluation value where 1=strongly disagree and 5=strongly agree (**Table 4.2**).

TH-1503_126105008

Table 4.2: Subjective questions towards System Usability

Item no.	Questions	Likert scale				
1.	I feel comfortable using this system	1	2	3	4	5
2.	It is helpful in modifying the design quickly before going for physical prototyping	1	2	3	4	5
3.	I believe I could become productive and efficient using this system	1	2	3	4	5
4.	It was easy to learn to use this system	1	2	3	4	5
5.	The system is effective in helping designers to complete their 3D form design task	1	2	3	4	5
6.	It was simple to use this system	1	2	3	4	5
7.	I am willing to use this system in future	1	2	3	4	5
8.	I would recommend to colleague to use this system	1	2	3	4	5
9.	This system may increase the Confidence of designer (s)	1	2	3	4	5
10.	With the point contact, is it good enough to evaluate virtual object	1	2	3	4	5

Ho_1: There is no significant difference in perceiving the haptic properties of virtual object with the variation of perceivers.

Ha_1: There is significant difference in perceiving the haptic properties of virtual object with the variation of perceivers.

The highest possible reliability coefficient is 1.0, but during reliability test (**Table 4.3)** the Cronbach's value for the ten items was 0.849, which is quite good comparing to the standard. Therefore consistencies of the scales (a set of questions) are reliable since it is greater than 0.70 as it is noted by (Field, 2009).

Item given SU1 to SU10, are questionnaires related to system usability and these questionnaires are shown above (**Table 4.2**).

TH-1503_126105008

Table 4.3: Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.849	.854	10

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
SU1	37.61	20.892	.563	.337	.834
SU2	37.14	22.003	.540	.460	.835
SU3	37.19	23.072	.478	.447	.841
SU4	37.15	22.831	.475	.446	.841
SU5	37.30	22.356	.575	.396	.833
SU6	37.13	21.224	.683	.549	.823
SU7	37.21	21.351	.644	.575	.826
SU8	37.10	22.063	.646	.566	.827
SU9	37.05	22.721	.544	.401	.836
SU10	37.87	22.019	.416	.288	.850

T-Test

Table 4.4: One-sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SU_AVG	84	4.141667	.5174563	.0564591

Table 4.5: One-Sample Test

	Test Value = 3					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
SU_AVG	20.221	83	.000	1.1416667	1.029372	1.253962

TH-1503_126105008

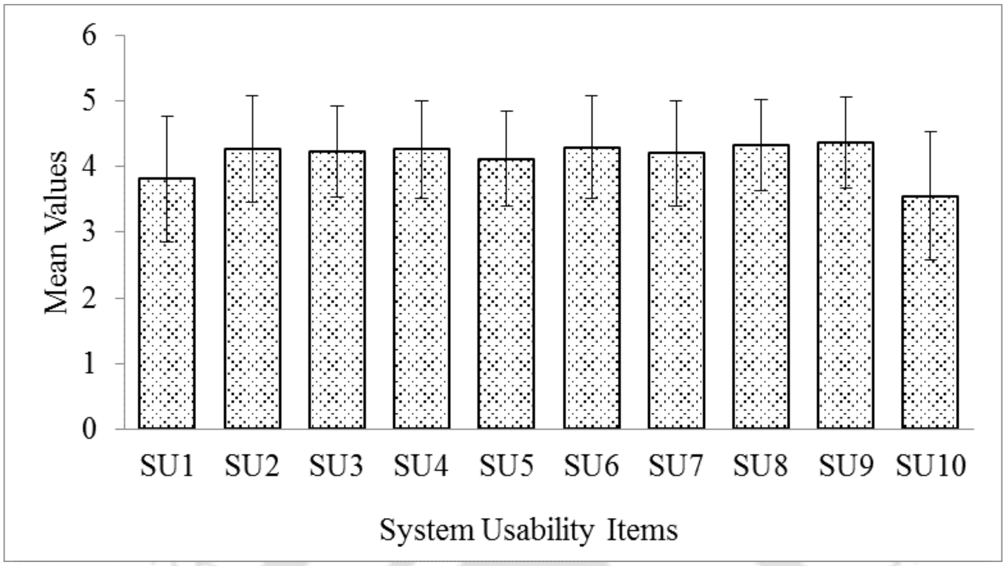


Figure 4.8: System usability Item Vs. Mean values

The *t*-test result shows in **Table 4.4** and **Table 4.5**, significantly most of the participant have rated more than three on 'System Usability' Scale (mean = 4.14; standard error = 0.0517) [t (83) =20.22; p<0.001]. Therefore, it is rejected the null hypotheses at least with 95% confidence level, this means most of the users agreed that the system is usable. In addition, as shown in **Figure 4.8** SU3 represent Subjective questions regarding the participants believe on this system in making designers' productive and efficient; and their response were positive, the statistical mean 4.2 > 3.0, and [t (83) =15.03; p<0.001].

4.4.4 Results related to system usability - objective measurement (haptic feedback device ability to give touch feelings)

(Perception of surface roughness, 3D form, weight and stiffness), questionnaires and hypothesis related to the ability of the device are shown below (**Table 4.6**).

Table 4.6: Objective questions towards system usability

Item no.	Questions	Likert scale				
11.	I am able to feel the stiffness of the virtual object	1	2	3	4	5
12.	I am able to feel the surface roughness of the virtual object	1	2	3	4	5
13.	I am able to feel the shape of virtual object	1	2	3	4	5
14.	The system gives weight perception of virtual object	1	2	3	4	5

TH-1503_126105008

Ho2: There is no significant difference in perceiving the roughness, weight, stiffness and 3D form of the virtual object with the variation of users.

Ha2: There is significant difference in perceiving the roughness, weight, stiffness and 3D form of the virtual object with the variation of users.

Table 4.7: Chi-square test

	SRoP	SWhtP	SStP	SShP
Chi-Square	51.714[a]	74.381[a]	31.357[b]	33.429[b]
df	3	3	2	2
Asymp. Sig.	.000	.000	.000	.000

We can see from **Table 4.7**; the Chi-square test statistic is statistically significant: [χ^2 (3) = 51.714, $p < .0001$], [χ^2 (3) = 74.381, $p < .0001$], [χ^2 (2) = 31.357, $p < .0001$], [χ^2 (2) = 33.429, $p < .0001$] Therefore, we can reject the null hypothesis and conclude that there are statistically significant differences in the preference to the scale above three with below three.

SRoP, SWhtP, SStP, and SShP abbreviation for questionnaires related to system usability in helping to perceive the roughness, weight, stiffness and 3D form of virtual object respectively.

T-Test

Table 4.8: One-Sample Test

	Test Value = 3					
			Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the difference	
Item	t	df			Lower	Upper
SRoP	14.459	83	.000	1.179	1.02	1.34
SWhtP	22.321	83	.000	1.488	1.36	1.62
SStP	17.321	83	.000	1.155	1.02	1.29
SShP	17.340	83	.000	1.143	1.01	1.27

TH-1503_126105008

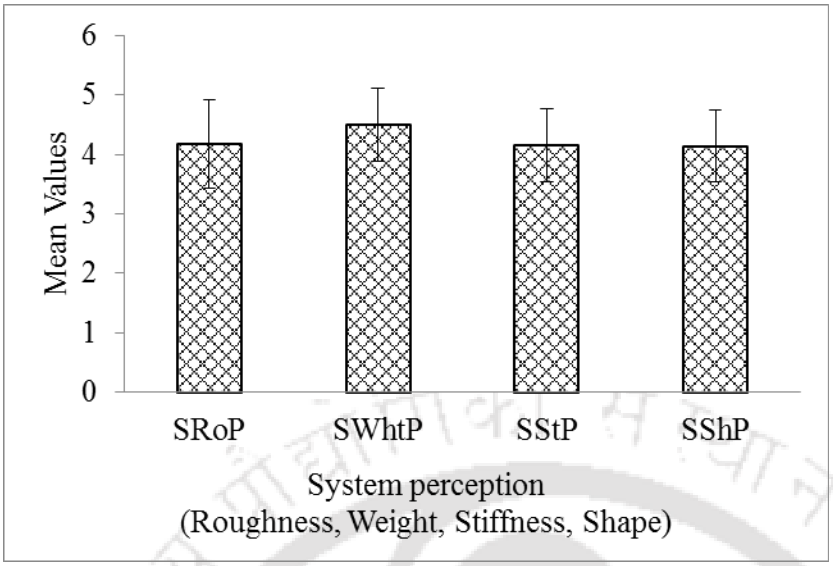


Figure 4.9: System perception Item Vs. Mean values

The t-statistical results were shown (**Table 4.8**); Significantly most of the participant have rated more than three on SRoP, SWhtP, SStP, SShP scale [t (83) = 14.459, p <0.001], [t (83) = 22.321, p <0.001], [t (83) = 17.321, p <0.001], [t (83) = 17.340, p <0.001] respectively. This means they were able to perceive the roughness, stiffness, weight, and 3D form of virtual object using Haptics feedback device. **Figure 4.9** shows the distribution of the mean values against system perception items.

Discussion (regarding result of system usability subjective and objective data results)

Sample consisted of 84 participants were evaluated the PHANToM Omni™ usability and ability in giving the feeling of the virtual object properties to the perceivers in all age groups and gender.

4.4.5 Statistical result of virtual object properties evaluation (surface texture, stiffness, weight, 3D form)

RQ15: I can sense the stiffness of carpets and bottles using the PHANToM Omni™

Ho3: There is no significant variation in perceived stiffness due to variation of stiffness level (Low Vs High) of the product or due to the combined effect of product type and stiffness level (carpet Vs bottle).

TH-1503_126105008

Ha3: There is significant variation in perceived stiffness due to variation of stiffness level (Low Vs High) of the product or due to the combined effect of product type and stiffness level (carpet Vs bottle).

Table 4.9: Chi-square test

	Perceived stiffness
Chi-Square	131.143[a]
df	4
Asymp. Sig.	.000

Table 4.10: Descriptive statistics of rating on level of stiffness

Level of stiffness	Product Type	Mean	Std. Deviation	N
	carpet	1.92	.542	84
	Bottle	1.85	.591	84
Perceived stiffness level Low	Total	1.88	.567	168
	carpet	4.05	.536	84
	Bottle	3.95	.536	84
Perceived stiffness level High	Total	4.00	.536	168

Table 4.11: Tests of within-subjects contrast

Measure: Perception stiffness

Source	stiffness level	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
stiffness level	Linear	377.190	1	377.190	1257.362	.000	.883
stiffness level * Product Type	Linear	.012	1	.012	.040	.842	.000

TH-1503_126105008

Table 4.12: Tests of Between-Subjects Effects

Measure: Level_of_stiffness

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	2905.190	1	2905.190	9414.356	.000	.983
Product Type	.583	1	.583	1.890	.171	.011

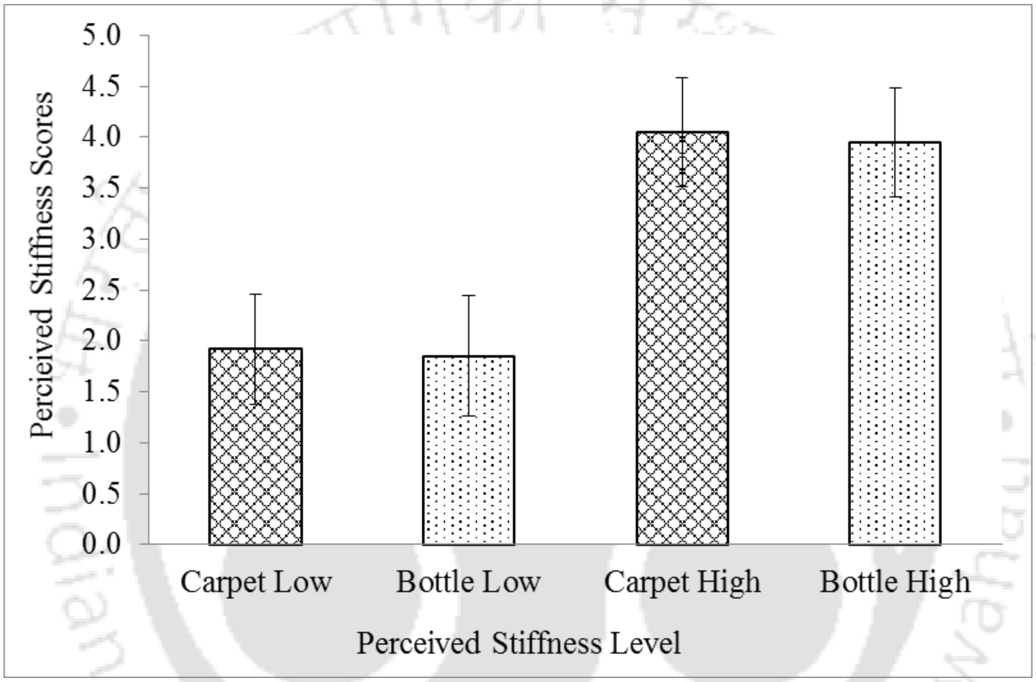


Figure 4.10: Perceived stiffness level Vs. Perceived stiffness level scores

As it is shown in **Table 4.9**; the Chi-square test statistic is statistically significant: [χ^2 (4) = 131.14, $p < .0001$]. Therefore, we can reject the null hypothesis and conclude that there are statistically significant differences in the preference to the scale above three with below three. It has been attempt to show the descriptive statistics the mean, standard deviation in **Table 4.10** and the distribution of the perceived stiffness level against perceived stiffness level score in **Figure 4.10**.

ANOVA hypothesis test was conducted for perception of stiffness, the combination of product type and level of stiffness. And from **Table 4.11** labeled test within-subjects

TH-1503_126105008

contrast and **Table 4.12** labeled test between-subjects effect gives the following ANOVA results.

There is no significant effect of product type on the perception of stiffness using PHANToM Omni™ [F (1,166) = 1.89, p>0.05, η^2_p=0.011].

There is no significant effect of combined effect of level of stiffness and product type on the perception of stiffness using PHANToM Omni™ [F (1,166) = 0.04, p>0.05, η^2_p=0.00].

There is significant variation of perceived stiffness due to the variation of level of stiffness [F (1,166) = 1257.36, p<0.001, η^2_p=0.883]. Therefore, there is a significant evidence to reject the null hypothesis.

Result: even though users of PHANToM Omni™ could significantly have perceived different levels of stiffness, the perception of stiffness was not varied significantly across product types. That means users can evaluate stiffness level of any product using phantom.

RQ16: I can sense the roughness of carpets using the PHANToM Omni™

Ho4: There is no significant variation in perceived the roughness due to variation of roughness levels (Low Vs High) of the product.

Ha4: There is significant variation in perceived the roughness due to variation of roughness levels (Low Vs High) of the product.

Table 4.13: Descriptive statistics of rating on level of roughness perception

	N	Mean	Std. Deviation	Min.	Max.
Perceived roughness _ Low	84	2.173	.5349	1.0	3.5
Perceived roughness _ High	84	3.893	.6356	2.0	5.0

Table 4.14: Chi-square test

	Perceived roughness Low	Perceived roughness High
Chi-Square	61.143[a]	72.333[b]
df	5	6
Asymp. Sig.	.000	.000

TH-1503_126105008

Table 4.15: Test Statistics

	Perceived roughness _Avg2 - Perceived roughness _Avg1
Z	-7.895[b]
Asymp. Sig. (2-tailed)	.000

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

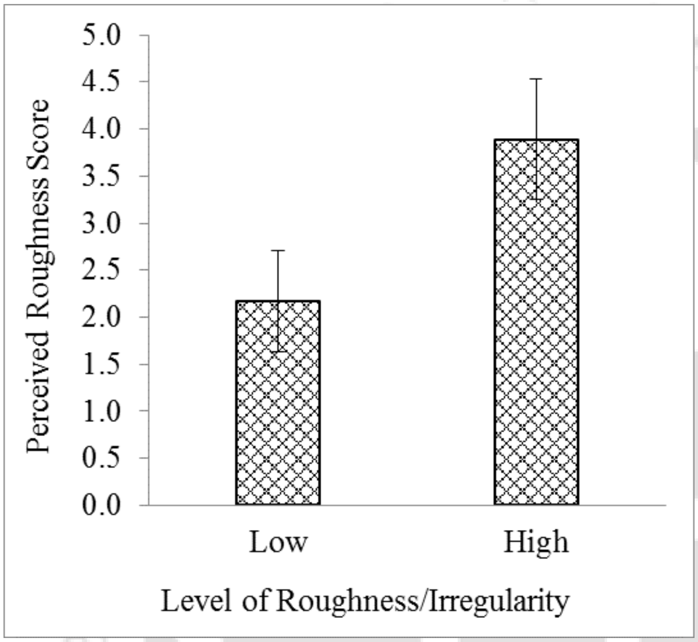


Figure 4.11: Level of roughness Vs. Perceived roughness score

Result: Table 4.14; chi-square test was conduct for internal consistency of responses given by participants and the result shows that most of the participant gave their responses less than three for perceived roughness level one, however, different participant rated the five-point scale in different ways depending on their perception about the roughness [χ^2 (5) = 61.143, p <0.001]. Similar result was also found in case of ratings given by participant for roughness level two, most of the participant gave their response greater than three [χ^2 (6) =72.33, p <0.001]. Therefore, it can be concluded that scales used to measure perceived roughness were reliable. To test the differences in perception of the roughness between products with different levels of roughness (low vs high) Wilcoxon signed ranks test was conducted. Result shows that there was significant

TH-1503_126105008

difference in roughness perception due to different levels of roughness [Z (83) = -7.895, $p < 0.001$], see **Table 4.15**. It has been attempt to show the descriptive statistics the mean, standard deviation in **Table 4.13** and the distribution of the level of roughness against perceived roughness level score in **Figure 4.11**.

RQ17: I can feel the 3D form of the following virtual object (water jar vs oil bottle)

Ho_5: There is no significant variation in perceived the 3D form due to variation of products.

Ha_5: There is significant variation in perceived the 3D form due to variation of products.

Table 4.16: Test Statistics

	3D form perception	3D form perception
Chi-Square	69.810[a]	66.952[b]
df	3	4
Asymp. Sig.	.000	.000

Table 4.17: Descriptive statistics of rating on shape perception

	N	Mean	Std. Deviation	Min.	Max.
3D form perception water jar	84	4.26	.679	1	5
3D form perception oil bottle	84	4.11	.932	1	5

Table 4.18: Test statistics

	3D form perception water jar - 3D form perception oil bottle
Z	-1.281
Asymp. Sig. (2-tailed)	.200

TH-1503_126105008

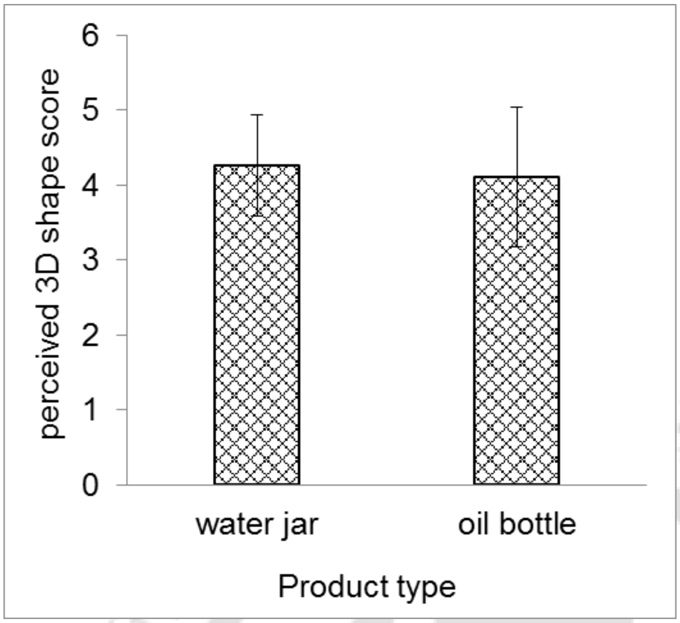


Figure 4.12: Product type Vs. Perceived 3D form score

Result: Table 4.16; chi-square test was conduct for internal consistency of responses given by participants and participants rated the five-point scale in different ways depending on their perception about the 3D Form. The result was as follows form of water jar [χ^2 (3) = 69.81, p <0.001] and form of oil bottle [χ^2 (4) =66.95, p <0.001]. Therefore, it can be concluded that scales used to measure perceived form of water jar and oil bottle were reliable. To test the differences in perception of the 3D form between products Wilcoxon signed ranks test was conducted. Result shows (**Table 4.18**) that there was no significant difference in the 3D form perception due to variation of product [Z (83) = -1.281, p = 0.200 (two-tailed)], Thus, the null hypothesis is accepted. This means the system can give perfect perception shape of virtual object whether it is flat and edged type or with curvier kind. In addition, it has been attempt to show the descriptive statistics the mean, standard deviation in **Table 4.17** and the distribution of perceived 3D form score against product type in **Figure 4.12**.

TH-1503_126105008

RQ18: I can sense the weight of tea leaf plucking machine using the PHANToM Omni™

Ho6: There is no significant variation in perceived the weight due to variation of levels of weight (Low Vs High) of the product.

Ha6: There is significant variation in perceived the weight due to variation of levels of weight (Low Vs High) of the product.

Table 4.19: Chi-square test

	Weight_perception_diff
Chi-Square	73.488[a]
df	4
Asymp. Sig.	.000

Table 4.20: Weight perception of tea leaf plucking machine_Low

Likert scale	Frequency	Percent	Valid percent	Cumulative percent
1	1	1.2	1.2	1.2
2	64	76.2	76.2	77.4
3	19	22.6	22.6	100
Total	84	100	100	

Table 4.21: Weight perception of tea leaf plucking machine_High

Likert scale	Frequency	Percent	Valid percent	Cumulative percent
4	50	59.5	59.5	59.5
5	34	40.5	40.5	100
Total	84	100	100	

Table 4.22: Descriptive statistics

	N	Mean	Std. Deviation	Min.	Max.
Weight perception of tea leaf plucking Machine_Low	84	2.21	.441	1	3
Weight perception of tea leaf plucking Machine_High	84	4.40	.494	4	5

TH-1503_126105008

Table 4.23: ANOVA

weight perception					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1287.054	1	1287.054	21.127	.000
Within Groups	10112.798	166	60.920		
Total	11399.851	167			

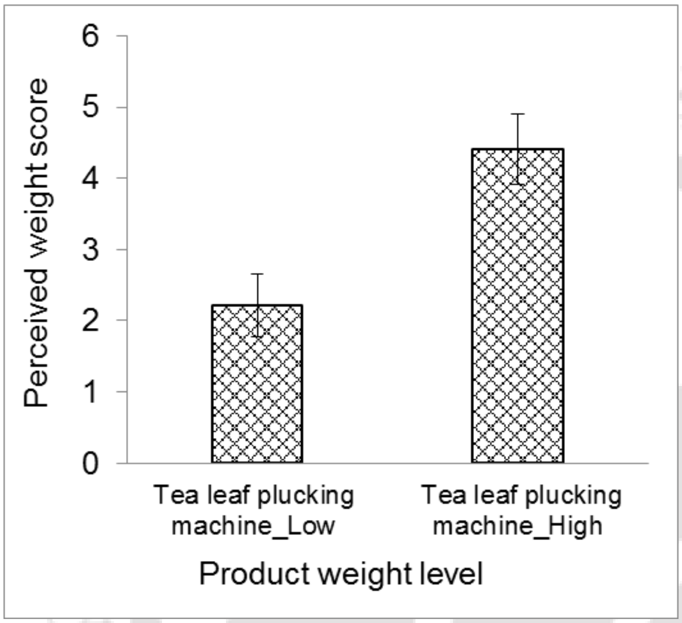


Figure 4.13: Product type (weight level) Vs. Perceived weight mean Score

Result: chi-square test was conduct for internal consistency of responses given by participants (**Tables 4.19 - 4.22**), however, different participant rated the five-point scale in different ways depending on their perception about the weight of tea leaf plucking [$\chi^2(4) = 73.488$, $p<0.001$. Therefore, it can be concluded that scales used to measure perceived weight of tea leaf plucking was reliable.

As it is shown in **Table 4.23**; a one-way ANOVA between subjects was conducted to compare the effect of the weight level (Low vs High) on the weight perception. Therefore, there was a significant effect of weight level on perception of the weight at the p <0.05 level for the three conditions [F = (1,166) =21.13, p <0.001]. Thus, the null hypothesis is rejected. In addition, it has been attempted to show the distribution of perceived weight score against product level (high, low) in **Figure 4.13**.

TH-1503_126105008

CHAPTER 5

5.0. Ergonomic Design modification, Testing and Evaluation of PHANToM Omni device stylus

In this chapter, discussion regarding the design of modification of the stylus, its prototyping based on the feedback of participants on the original stylus during the earlier experiments has been incorporated. Modification of design of stylus is to reduce discomfort and pain/strain reported by participants earlier on the participants' hands and to improve task precision and efficiency. In addition to these, Wilcoxon test was used to analyze the data collected to draw the actual conclusions of the participants' preference/feeling regarding the modified stylus for texture and weight perception. Wilcoxon test is good for the same participants on two conditions/activity for skewed distribution.

5.1. Design and Manufacturing procedure

During design stage, four different alternative models with improved gripping diameter, shape and pressing options, as depicted in **Figure 5.1, Figure 5.2, Figure 5.3** and **Figure 5.4** were created. Among the four conceptual design two were selected (heuristic evaluation) for detail drawing and development, shown in **Figure 5.3** and **Figure 5.4**. During this some criteria, such as manufacturing cost, easy to grip and fit on the original stylus, complexity, aesthetics, etc. based on the intended objective of the product were set. Thereafter, it was started to prototype these for experimental purpose. Prototype were made in studio of Department of Design by developing pattern using woods that gives the outer shape and keeps the cavity to fit the newly developed stylus on the original stylus, during this the wood pattern were split in to two as shown in **Figure 5.5**. Finally, it was used for plastic vacuum forming machine to produce the product from HIPS (High Impact Polystyrene) sheet with 3mm thickness and joining gum were used to join the split parts to get the final prototype depicted in **Figure 5.6**. and **Figure 5.7**.

TH-1503_126105008

Figure 5.1: Proposed product model one

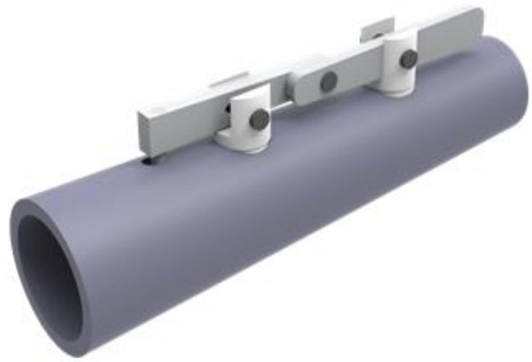


Figure 5.2: Proposed product model two

Figure 5.3: Proposed product model three

Figure 5.4: Proposed product model four

Institute of Technology

TH-1503_126105008

Figure 5.5: Wood pattern for making the modified stylus from plastic

Figure 5.6: Prototype stylus with thumb pressing (Stylus 1)

TH-1503_126105008

Figure 5.7: Prototype stylus with palm pressing (Stylus 2)

5.2. Usability Testing Procedure

Among participants who were involved in the first experiments, 31 students were approached and asked to examine the modified stylus with thumb pressing and with palm pressing and give their feedback. The setup consists of perceiver, haptic device (PHANToM Omni™), virtual object/environment and haptic interface as it were in the previous experiment mentioned in chapter four. In order understand users' feeling towards the modified stylus it was provided post-task questionnaire to be filed by participants with the aim of perceiving:

1. its easiness and comfort during rubbing on the surface and perceiving the surface texture of the bottle and
2. Light weightiness easiness and painlessness during griping and lifting the tea leaf plucking machine model.

This experiment was conducted by allowing participants to interact with the virtual object and feel the surface texture of the bottle and perceive the weight of the tea leaf plucking machine model through the modified stylus which is fitted on the original stylus, as depicted in **Figure 5.8** and **Figure 5.9**. Those virtual models were selected among the previous models targeting to perceive the modified stylus comfortability during rubbing on the surface and lifting the aforementioned virtual objects. Its main aim was to compare

TH-1503_126105008

this two modified stylus with the previous feedback given by respondents' and decide better stylus for future implementation. Each participant spent ten to fifteen minutes time for evaluating the virtual prototype properties. The participants were from Department of Design and Department of Mechanical Engineering of IIT Guwahati.

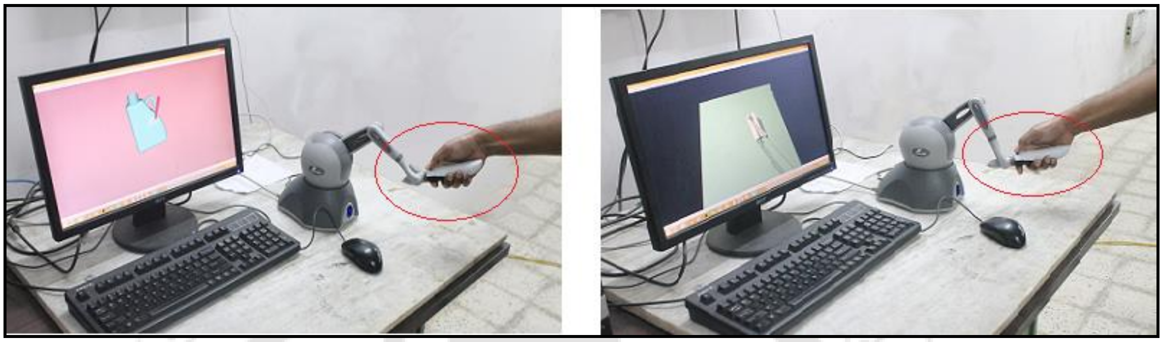


Figure 5.8: Modified stylus with thumb pressing fitted over original stylus

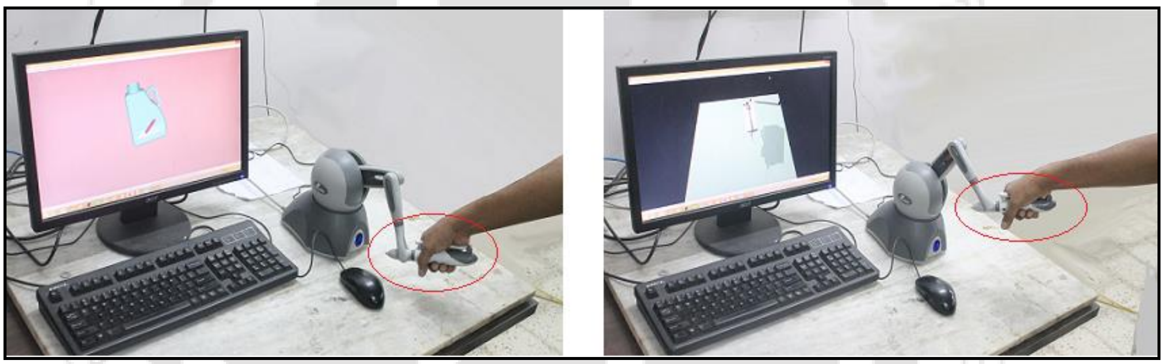


Figure 5.9: Modified stylus with palm pressing fitted over original stylus

Questionnaires preparation

Questionnaires were prepared with 5-point Likert scale and open-ended questions focused on the usability of the modified stylus, the virtual object evaluation and general information of the respondents such as demographical information and academic background. Full questionnaires shown in appendix D.

TH-1503_126105008

5.3. Participants background, Sex and data analysis procedures

To observe the results of experimental based data, it has been started by identifying the type of variables (independent and dependent variables), number of variables and number of samples with appropriate steps to be used during data analysis.

Procedure followed to analyze the statistical data

1. checking the normal distribution of data or sample characteristics (Shapiro-Wilk test P-value test, and visually inspection the histograms, normal Q-Q plots),
2. Reliability of the scale using Cronbach's alpha,
3. Description statistics (Mean, SD, Frequency, percentile, etc.),
4. Inferential statistics Wilcoxon signed rank test, Z-test.

5.3.1 Descriptive statistics of the respondents' demography profile

As depicted in the **Figure 5.10** and **Figure 5.11**, considering the nominal variables it was attempted to show the age and gender distribution of the participants. Among the 31 respondents' 6 were females (19.4%) and 25 were males (80.6%), with in the age range of twenty to forty (Age 20-30 were 20 (64.5%) and Age above 30 were 11 (36.5%) of the total participant).

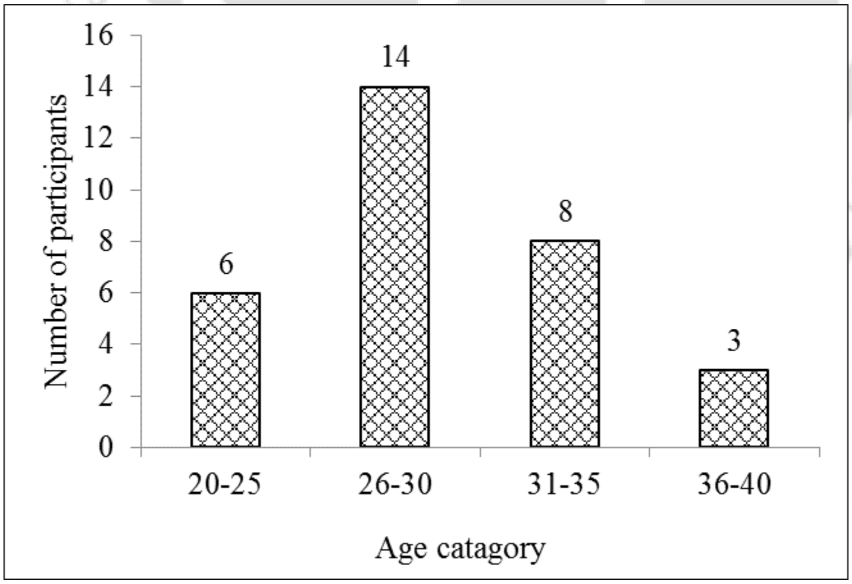


Figure 5.10: Distribution of participants by age group

TH-1503_126105008

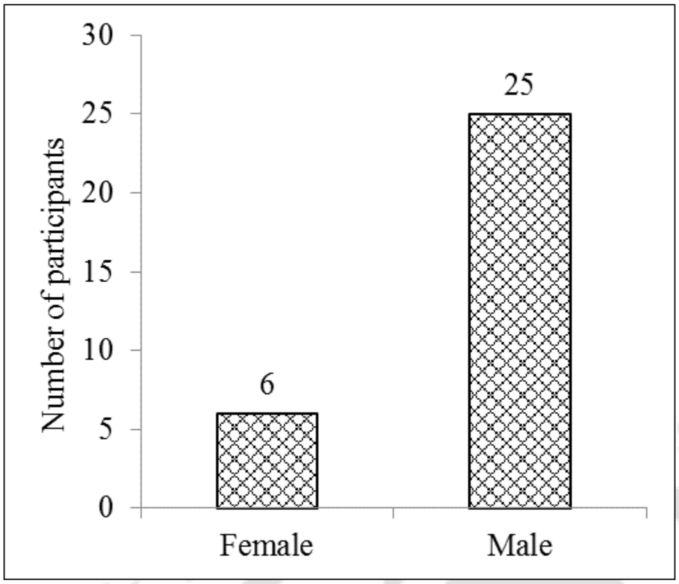


Figure 5.11: Distribution of participants by gender

5.3.2 Participant's Educational qualification

As depicted in **Figure 5.12**, participant with current academic enrollment from M.Des. were 9 participants (29%), PhD from both departments were 21 participants (67.8%) and one postdoc (3.2%) from Department of Design;

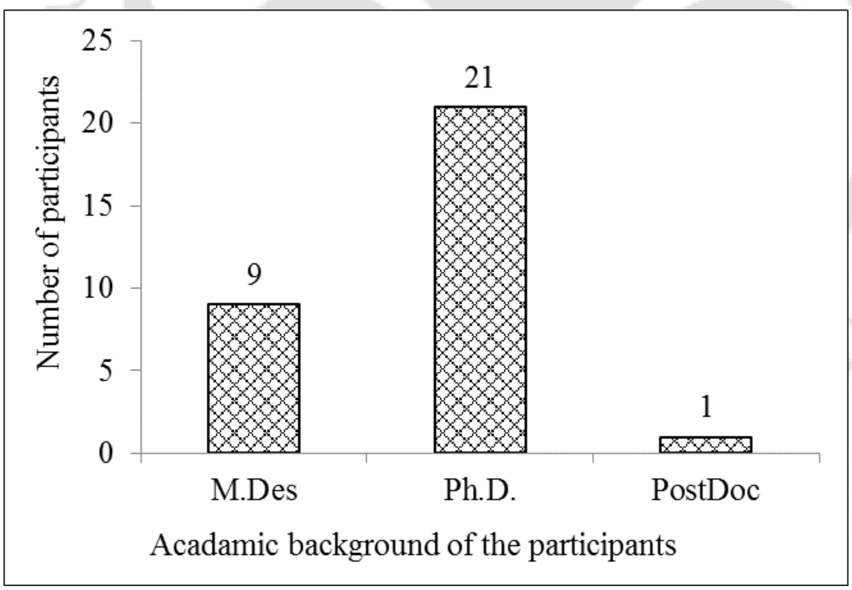


Figure 5.12: Educational qualification of participants

TH-1503_126105008

5.3.3 Reliability of the scale

It has been evaluated the internal consistency and strength of the set questioners/items through a coefficient of reliability test that is Cronbach's alpha coefficient and the Cronbach's alpha value for the eight items was 0.738, which is quite good comparing to the standard. Therefore, consistencies of the scales for the set of questions are reliable as depicted in **Table 5.1**.

Table 5.1: Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.738	.735	8

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
I am able to feel the surface roughness of the virtual object	28.64	10.75	.392	.422	.718
I am able to feel the weight of the virtual object	28.30	11.26	.348	.441	.726
I felt comfortable using this stylus	28.87	11.26	.341	.308	.727
it was easy to grip	28.83	10.82	.466	.306	.705
it was comfortable and easy	29.03	9.76	.537	.383	.688
it is light weight and comfortable to perceive the texture of the virtual object	28.85	10.94	.385	.237	.719
it is light weight and comfortable to perceive the weight of the virtual object	28.6129	10.569	.442	.426	.709
it doesn't give any pain	28.9355	9.504	.530	.340	.689

TH-1503_126105008

5.4. Results of Usability testing

SPSS Statistical tool were used to investigate participant's preference in selecting better one among the two modified stylus with different pressing options. This was conducted by giving and demanded to fill the post-test questionnaire with 5 points Likert's scale. The Wilcoxon signed-rank test were used for comparison the two sets of scores and assess for significant differences that come from the same participants. This has been done to investigate any difference in score of the perception, lightness, comfortability and painlessness of the product shape and pressing option provided.

RQ1: I am able to feel the surface roughness of the virtual object.

Ho1: There will be no significant difference in perceiving the surface roughness of the virtual object due to the variation of Stylus 1 and Stylus 2.

Ha1: There will be significant difference in perceiving the surface roughness of the virtual object due to the variation of stylus 1 and stylus 2.

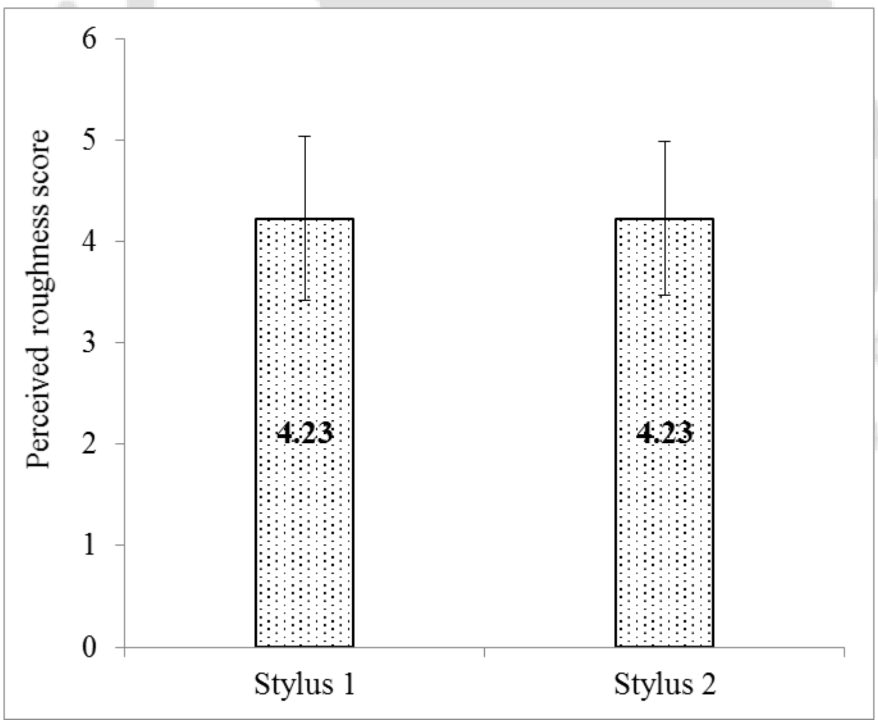


Figure 5.13: Stylus type Vs. Perceived roughness score

TH-1503_126105008

Wilcoxon Signed Ranks Test

Table 5.2: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2- Stylus 1	Negative Ranks	7[a]	7.50	52.50
	Positive Ranks	7[b]	7.50	52.50
	Ties	17[c]		
	Total	31		

a. Stylus 2< Stylus 1
b. Stylus 2> Stylus 1
c. Stylus 2= Stylus 1

Table 5.3: Test Statistics[a]

	Stylus 2- Stylus 1
Z	.000[b]
Asymp. Sig. (2-tailed)	1.000

a. Wilcoxon Signed Ranks Test
b. The sum of negative ranks equals the sum of positive ranks.

As it is shown the legend in **Table 5.2**, 7 participants preferred Stylus 1 than Stylus 2, 7 participants preferred Stylus 2 than Stylus 1, and 17 participants rated the same for both Styluses. There is no significant difference in perceiving the roughness due to the change between the two stylus as shown in the test statistics **Table 5.3** Asymp. Sig (2-tailed) value which is 1.000, therefore Null hypothesis is accepted. **Figure 5.13** shown to display the distribution of perceived roughness score against stylus type.

RQ2: I am able to feel the weight of the virtual object.

Ho2: There will be no significant difference in perceiving the weight of the tea leaf plucking machine model due to the variation of Stylus 1 and Stylus 2.

Ha2: There will be significant difference in perceiving the weight of the tea leaf plucking machine model due to the variation of Stylus 1 and Stylus 2.

TH-1503_126105008

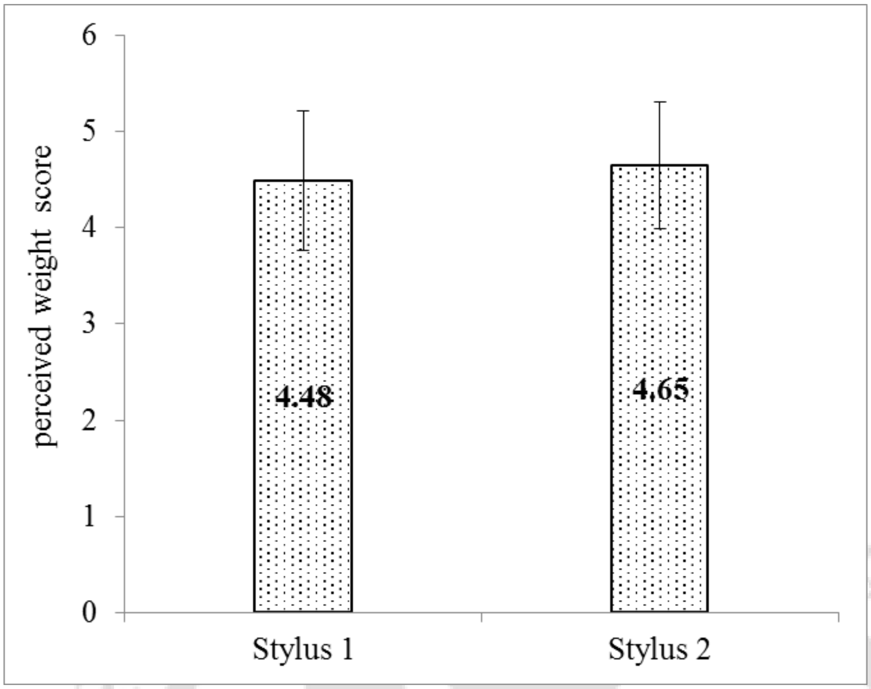


Figure 5.14: Stylus type Vs. Perceived weight score

Wilcoxon Signed Ranks Test

Table 5.4: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	4[a]	5.00	20.00
	Positive Ranks	7[b]	6.57	46.00
	Ties	20[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 5.5: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-1.232[b]
Asymp. Sig. (2-tailed)	.218

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

TH-1503_126105008

As it is shown the legend in **Table 5.4**, 4 participants preferred Stylus 1 than Stylus 2, 7 participants preferred Stylus 2 better than Stylus 1 and 20 participants rated the same for both styluses. There is minor difference by three score by participants which preferred Stylus 2 but as shown in the test statistics **Table 5.5** Asymp. Sig (2-tailed) value which is .218, [Z = -1.232, p =.218], does not affect the total score, therefore Null hypothesis is accepted. **Figure 5.14** shown to display the distribution of perceived weight score against stylus type.

RQ3: It is easy and comfortable to use this stylus.

Ho3: There will be no significant difference in easiness and comfortability feeling due to the variation of Stylus 1 and Stylus 2.

Ha3: There will be significant difference in easiness and comfortability feeling due to the variation of Stylus 1 and Stylus 2.

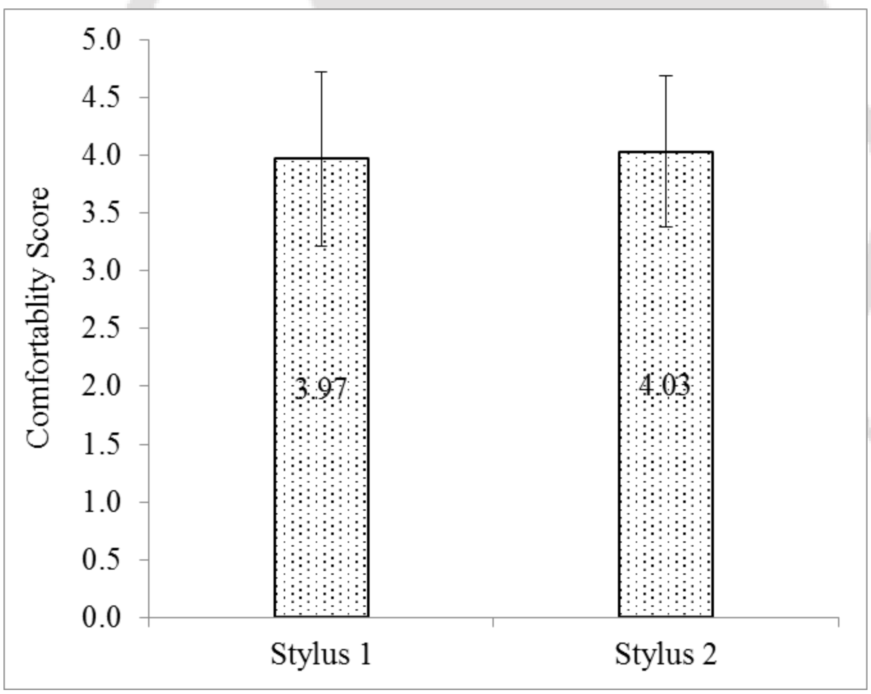


Figure 5.15: Stylus type Vs. Comfortability score

TH-1503_126105008

Wilcoxon Signed Ranks Test

Table 5.6: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2- Stylus 1	Negative Ranks	12[a]	11.50	138.00
	Positive Ranks	12[b]	13.50	162.00
	Ties	7[c]		
	Total	31		

a. Stylus 2< Stylus 1
b. Stylus 2> Stylus 1
c. Stylus 2= Stylus 1

Table 5.7: Test Statistics[a]

	Stylus 2- Stylus 1
Z	-.369[b]
Asymp. Sig. (2-tailed)	.712

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

As it is shown the legend in **Table 5.6**, 12 participants preferred Stylus 1 than Stylus 2, 12 participants preferred Stylus 2 better than Stylus 1 and 7 participants rated the same for both styluses. There is no significant difference as shown in **Table 5.7** Asymp. Sig (2-tailed) value which is .712, [Z = -.369, p =.712], therefore Null hypothesis is accepted. **Figure 5.15** shown to display the distribution of comfortable score against stylus type.

RQ4: It was easy to grip.

Ho4: There will be no significant difference in gripping the virtual object due to the variation of Stylus 1 and Stylus 2.

Ha4: There will be significant difference in gripping the virtual object due to the variation of Stylus 1 and Stylus 2.

TH-1503_126105008

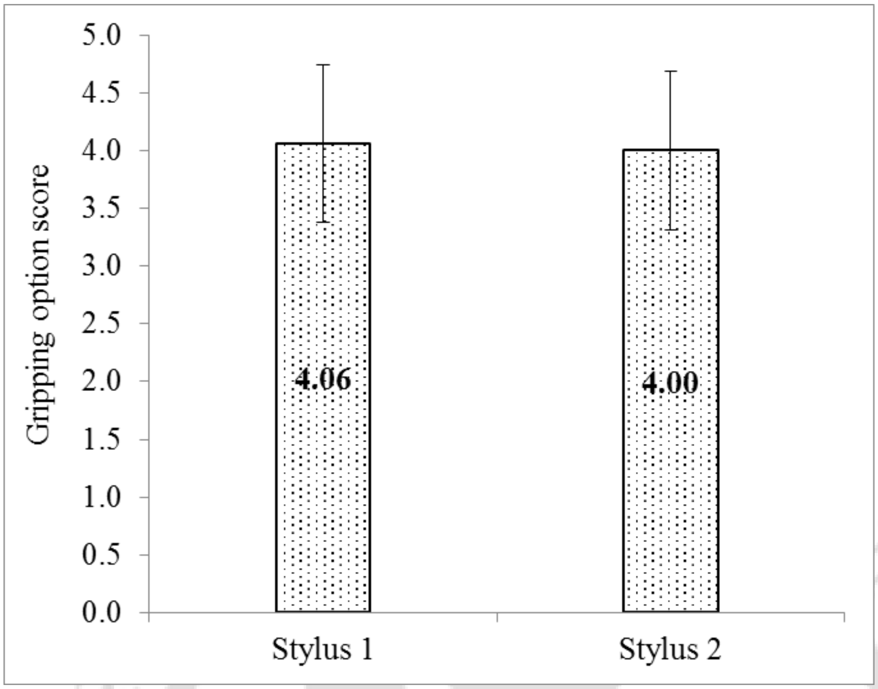


Figure 5.16: Stylus type Vs. Griping option score

Wilcoxon Signed Ranks Test

Table 5.8: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	11[a]	10.41	114.50
	Positive Ranks	9[b]	10.61	95.50
	Ties	11[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 5.9: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-.389[b]
Asymp. Sig. (2-tailed)	.697

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.

TH-1503_126105008

As it is shown the legend in **Table 5.8**, 11 participants preferred Stylus 1 than Stylus 2, 9 participants preferred Stylus 2 better than Stylus 1 and 11 participants rated the same for both styluses. There is minor difference by two score which preferred Stylus 2 but as shown in the test statistics **Table 5.9** Asymp. Sig (2-tailed) value which is .697, [$Z = -.389$, $P = .697$], does not affect the total score, therefore Null hypothesis is accepted. **Figure 5.16** depict the distribution of griping score against stylus type.

RQ5: It is light weight and comfortable to perceive the texture of the virtual object.

Ho5: There will be no significant difference between the stylus 1 and stylus 2 in lightness and comfortability.

Ha5: There will be significant difference between the stylus 1 and stylus 2 in lightness and comfortability.

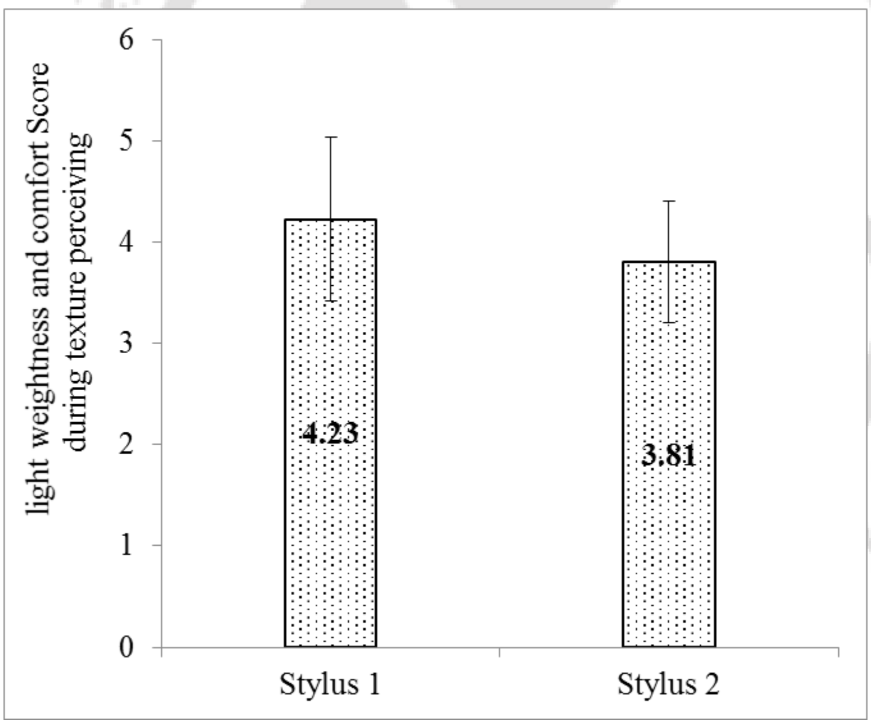


Figure 5.17: Stylus type Vs. Lightness and Comfortability Score

TH-1503_126105008

Wilcoxon Signed Ranks Test

Table 5.10: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	15[a]	10.27	154.00
	Positive Ranks	4[b]	9.00	36.00
	Ties	12[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 5.11: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-2.599[b]
Asymp. Sig. (2-tailed)	.009

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.

As it is shown the legend in **Table 5.10**, 15 participants preferred Stylus 1 than Stylus 2, 4 participants preferred Stylus 2 better than Stylus 1and 12 participants rated the same for both styluses. There is significant difference by 11 score which preferred Stylus 1 as a light weight and comfortable to handle during rubbing the surface, as shown in the test statistics **Table 5.11** Asymp. Sig (2-tailed) value which is .009, [Z = -2.599, P<.05], therefore Null hypothesis rejected. **Figure 5.17** shown to display the distribution of Lightness and Comfortability score against stylus type during texture perception.

RQ6: It is light weight and comfortable to perceive the weight of the virtual object

Ho6: There will be no significant difference between the stylus1 and stylus 2 in lightness and comfortability.

Ha6: There will be significant difference between the stylus 1 and stylus 2 in lightness and comfortability.

TH-1503_126105008

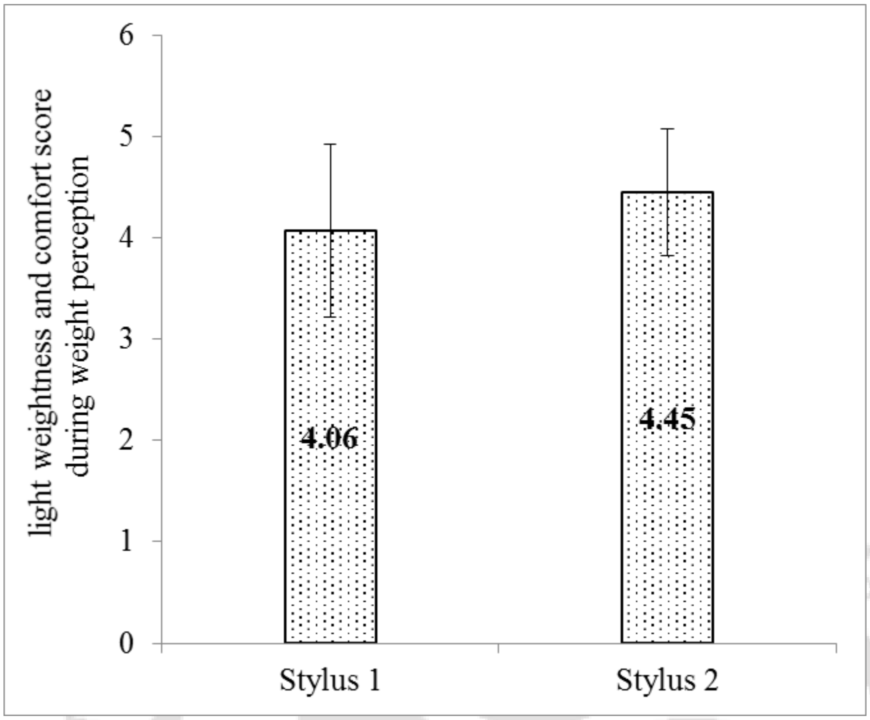


Figure 5.18: Stylus type Vs. Lightness and Comfortability Score

Wilcoxon Signed Ranks Test

Table 5.12: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	5[a]	10.90	54.50
	Positive Ranks	15[b]	10.37	155.50
	Ties	11[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 5.13: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-2.036[b]
Asymp. Sig. (2-tailed)	.042

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

TH-1503_126105008

As it is shown the legend in **Table 5.12**, 5 participants preferred Stylus 1 than Stylus 2, 15 participants preferred Stylus 2 better than Stylus 1 and 11 participants rated the same for both styluses. There is significant difference by 10 scores which preferred Stylus 2 as a light weight and comfortable to handle during weight lifting as shown in the test statistics **Table 5.13** Asymp. Sig (2-tailed) value which is .042, [Z = -2.036, P<.05], therefore Null hypothesis rejected. **Figure 5.18** shown to display the distribution of Lightness and Comfortability score against stylus type during weight perception.

RQ7: It doesn't give any pain.

Ho_7: There will be no significant difference in wrist discomfort level due to the variation of the Styluses.

Ha_7: There will be significant difference in wrist discomfort level due to the variation of the Styluses.

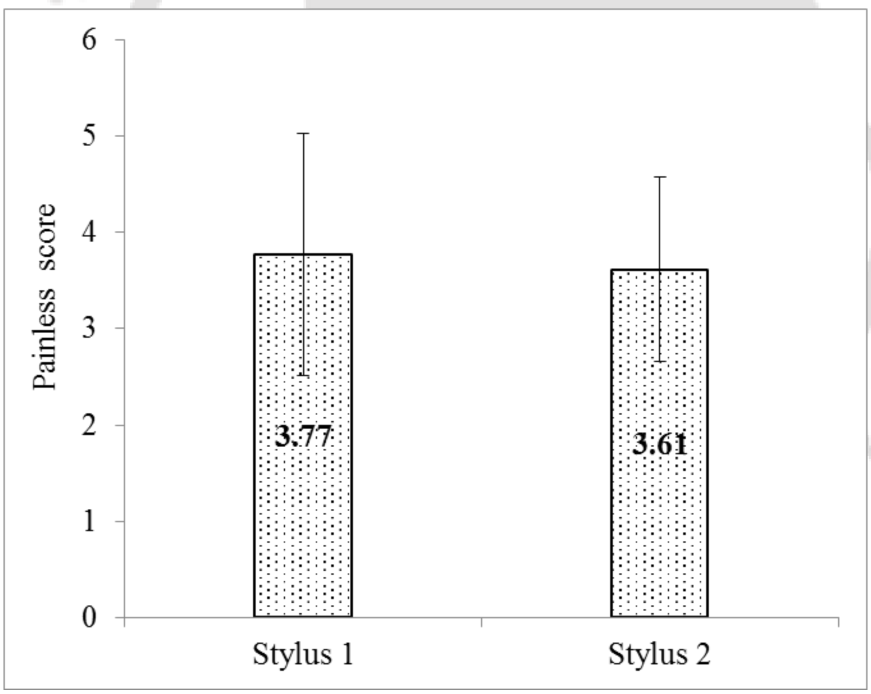


Figure 5.19: Stylus type Vs. wrist discomfort score

TH-1503_126105008

Wilcoxon Signed Ranks Test

Table 5.14: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	9[a]	8.89	80.00
	Positive Ranks	9[b]	10.11	91.00
	Ties	13[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 5.15: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-.251[b]
Asymp. Sig. (2-tailed)	.802

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

As it is shown the legend in **Table 5.14**, 9 participants preferred Stylus 1 than Stylus 2, 9 participants preferred Stylus 2 better than Stylus 1 and 13 participants rated the same for both products. There is no significant difference as shown in the test statistics **Table 5.15** Asymp. Sig (2-tailed) value which is .802 [Z = -.251, P =.802], therefore Null hypothesis is accepted. **Figure 5.19** shown to depict the distribution of wrist discomfort score against stylus type

Discussion and conclusion

In this chapter it has attempt to show the procedure followed to develop and manufacture the modified stylus and shown the final version of the product. it was also demonstrated the participants academic background, gender composition and questionnaire internal consistency using Cronbach's alpha coefficient. Furthermore, the descriptive statistics and inferential statistics has been shown in detail. Finally, Wilcoxon signed rank test has been used to determine whether there was a difference in ranking of the two Styluses by participants. Results of that analysis indicated that there was a significant difference

TH-1503_126105008

between stylus 1 and stylus 2 in giving the accurate feeling to the user with comfort gripping and optimum cylindrical handling diameter to rub on the surface and lift the virtual object. Stylus 1 were preferred stylus as a better option for surface rubbing, [$Z = -2.599$, $P < .05$] and stylus 2 were preferred stylus as a better option for weight lifting, [$Z = -2.036$, $P < .05$].

Indian Institute of Technology Guwahati

TH-1503_126105008

CHAPTER 6

6.0. Discussions and contribution of the study; Conclusion and Recommendation

6.1. Discussions

This research work briefly discussed about VR and haptic feedback device technologies and their applications in various design related fields. It also discussed about the benefits of integration of haptic feedback device into the VR systems as well as how these integrated systems would help designers to perform realistically in complex computer aided product design process. A method has been formulated to create virtual object using various CAD softwares (CATIA in this case) and conversion to X3D data format in order to apply evaluation functions of haptic interaction by employing SensAble OpenHaptics toolkit. Thereafter, it has been discussed regarding the experimental setup, data collection, data analysis and interpret results related to the usability of the PHANToM Omni™ and tactile perception of different virtual objects shape, surface texture, stiffness, and weight. During this experiment, it was observed that the styles of the PHANTOM Omni™ represented by the proxy to touch the virtual object i.e. point contact and this may not give exactly the expected perceptional feeling what we expect in our mind. In addition to this during the experiment participants were complaining and expressed their dissatisfaction due to the size of the stylus and griping like a pen that gives pain on their wrist when they practiced for prolonged time. However, this experiment gives users the feeling to differentiate the surface texture and stiffness, weight of different virtual objects as the result of data analysis show. Based on the experimental finding, attempt was made to solve the problem and provide alternative stylus by designing modified version of stylus that fitted on the existing system (PHANToM Omni™). Further experiments were conducted to understand and compare the modified stylus' usability in terms of ease and comfortability to rub the bottle; grip and lift the tea leaf plucking machine model and perceive the weight of the machine.

To sum up the overall experiment, statistical analysis was conducted using the data obtained from the same participants for the three styluses; these are: modified stylus 1

TH-1503_126105008

(stylus with thumb pressing), stylus 2 (stylus with palm pressing) and original stylus. To get the comparative preference rank of the three styluses, Friedman's test was used as it is easy and better for comparing more than two groups and results were shown below in table 6.1 to table 6.18.

6.1.1. Descriptive statistics and Freidman's test for comparing the stylus comfortability to rub and perceive surface roughness of the bottle.

Ho$_1$: There will be no significant difference between the three stylus due to shape and pressing options on the perception of comfortability during rubbing.

Ha$_1$: There will be significant difference between the three stylus due to shape and pressing options on the perception of comfortability during rubbing.

Table 6.1: Descriptive statistics of rating on stylus comfortability preference

						Percentiles		
Stylus name	N	Mean	Std. Deviation	Min.	Max.	25th	50th (Median)	75th
Stylus 1	31	4.2258	.80456	2.00	5.00	4.0000	4.0000	5.0000
Stylus 2	31	4.2258	.76200	2.00	5.00	4.0000	4.0000	5.0000
Original stylus	31	4.1613	.86011	2.00	5.00	4.0000	4.0000	5.0000

Friedman Test

Table 6.2: Ranks

Stylus name	Mean Rank
Stylus 1	2.02
Stylus 2	2.00
Original stylus	1.98

Table 6.3:Test Statistics[a]

N	31
Chi-Square	.028
df	2
Asymp. Sig.	.986

a. Friedman Test

A Friedman's test was conducted to determine whether participants had a differential rank ordered preference for the three stylus based on their comfort to rub and feel the surface texture. In addition to the final result, descriptive statistics and mean ranks respectively depicted in **Table 6.1** and **Table 6.2**. As the result of the analysis indicated in **Table 6.3**, there is no significant difference among the three styluses (stylus 1, stylus 2 and original stylus) $\chi^2(2, N=31) = .028$, $p>0.05$.

TH-1503_126105008

From Friedman test $\chi^2(2)$ =.028, p=.986, we can conclude that three of the styluses may give the same feeling in comfortability during rubbing/surface texture perceiving process. And in this situation it is not important to conduct pairwise Wilcoxon tests to understand the favorable rankings difference among the three types of stylus.

6.1.2. Descriptive statistics and Freidman's test for comparing the stylus comfortability to lift and perceive the weight of the tea leaf plucking machine model.

Ho2: There will be no significant difference between the three stylus due to shape and pressing options on the perception of comfortability during weight lifting.

Ha2: There will be significant difference between the three stylus due to shape and pressing options on the perception of comfortability during weight lifting.

Table 6.4: Descriptive statistics of rating on stylus comfortability preference

						Percentiles		
Stylus name	N	Mean	Std. Deviation	Min.	Max.	25th	50th (Median)	75th
Stylus 1	31	4.0645	.85383	2.00	5.00	4.0000	4.0000	5.0000
Stylus 2	31	4.4516	.62390	3.00	5.00	4.0000	5.0000	5.0000
Original stylus	31	3.7097	.58842	3.00	5.00	3.0000	4.0000	4.0000

Friedman Test

Table 6.5: Ranks

Stylus name	Mean Rank
Stylus 1	2.00
Stylus 2	2.42
Original stylus	1.58

Table 6.6: Test Statistics[a]

N	31
Chi-Square	16.095
df	2
Asymp. Sig.	.000

a. Friedman Test

A Friedman's test was conducted to determine whether participants had a differential rank ordered preference for the three styluses based on their comfort, easiness to grip and press the button. In addition to the final result, descriptive statistics and mean ranks respectively depicted in **Table 6.4** and **Table 6.5**. As the result of the analysis indicated in **Table 6.6**, there is an overall difference among the three styluses (stylus 1, stylus 2 and

TH-1503_126105008

original stylus) $\chi^2(2, N=31) = 16.095$, $p<0.05$. it is also important to conduct series of Wilcoxon tests to identify where the rank ordered preferences for the three styluses. we will need pair wise comparisons to identify which stylus are different from which others. To do this, it was conducted Wilcoxon signed rank test as shown below.

Stylus 1 Vs. Stylus 2

Table 6.7: Descriptive Statistics

Stylus name	N	Mean	Std. Deviation	Min.	Max.	Percentiles 25th	Percentiles 50th (Median)	Percentiles 75th
Stylus 1	31	4.0645	.85383	2.00	5.00	4.0000	4.0000	5.0000
Stylus 2	31	4.4516	.62390	3.00	5.00	4.0000	5.0000	5.0000

Wilcoxon Signed Ranks Test

Table 6.8: Ranks

		N	Mean Rank	Sum of Ranks
Stylus 2 - Stylus 1	Negative Ranks	5[a]	10.90	54.50
	Positive Ranks	15[b]	10.37	155.50
	Ties	11[c]		
	Total	31		

a. Stylus 2 < Stylus 1
b. Stylus 2 > Stylus 1
c. Stylus 2 = Stylus 1

Table 6.9: Test Statistics[a]

	Stylus 2 - Stylus 1
Z	-2.036[b]
Asymp. Sig. (2-tailed)	.042

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks.

TH-1503_126105008

Stylus 1Vs. Original Stylus

Table 6.10: Descriptive statistics

Stylus name	N	Mean	Std. Deviation	Min.	Max.	Percentiles 25th	50th (Median)	75th
Stylus 1	31	4.0645	.85383	2.00	5.00	4.0000	4.0000	5.0000
Original stylus	31	3.7097	.58842	3.00	5.00	3.0000	4.0000	4.0000

Wilcoxon Signed Ranks Test

Table 6.11: Ranks

		N	Mean Rank	Sum of Ranks
Original stylus - Stylus 1	Negative Ranks	16[a]	11.13	178.00
	Positive Ranks	6[b]	12.50	75.00
	Ties	9[c]		
	Total	31		

a. Original stylus < Stylus 1
b. Original stylus > Stylus 1
c. Original stylus = Stylus 1

Table 6.12: Test Statistics[a]

	Orignal stylus - Stylus 1
Z	-1.755[b]
Asymp. Sig. (2-tailed)	.079

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.

Stylus 2 Vs. Original Stylus

Table 6.13: Descriptive statistics

Stylus name	N	Mean	Std. Deviation	Min.	Max.	Percentiles 25th	50th (Median)	75th
Stylus 2	31	4.4516	.62390	3.00	5.00	4.0000	5.0000	5.0000
Original stylus	31	3.7097	.58842	3.00	5.00	3.0000	4.0000	4.0000

TH-1503_126105008

Wilcoxon Signed Ranks Test

Table 6.14: Ranks

		N	Mean Rank	Sum of Ranks
Original stylus - Stylus 2	Negative Ranks	16[a]	8.50	136.00
	Positive Ranks	0[b]	.00	.00
	Ties	15[c]		
	Total	31		

a. Original stylus < Stylus 2
b. Original stylus > Stylus 2
c. Original stylus = Stylus 2

Table 6.15: Test Statistics[a]

	Orignal stylus - Stylus 2
Z	-3.624[b]
Asymp. Sig. (2-tailed)	.000

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.

Summary:

As it is shown the pairwise Wilcoxon test statistics: Stylus 1 Vs. Stylus 2, in **Table 6.9**, z=-2.036, p<.05; Stylus 1 Vs. original Stylus, in **Table 6.12**, z=-1.755, p>.05 or z=-1.755, p=.079; and Stylus 2 vs. Original Stylus, in **Table 6.15**, z=-3.624, p<.05.

There were significantly difference among the distribution of the three types of styluses based on the Friedman test $\chi^2(2)$ =16.33, p=0.605, and pairwise Wilcoxon tests (p<.05) revealed that, as Stylus 2 were more favorable rankings than either stylus 1 or original stylus. In addition, the final Friedman test, the descriptive statistics and mean ranks of the three pairwise Wilcoxon test respectively depicted in **Table 6.7** and **Table 6.8**; **Table 6.10** and **Table 6.11; Table 6.13** and **Table 6.14.**

6.1.3. Descriptive statistics and Freidman's test for comparing overall easiness and comfortability of the stylus.

Ho3: There will be no significant difference between the three styluses due to shape and pressing options on the perception of overall ease of use and comfortability**.**

TH-1503_126105008

Ha3: There will be significant difference between the three styluses due to shape and pressing options on the perception of overall ease of use and comfortability.

Table 6.16: Descriptive statistics

Stylus name	N	Mean	Std. Deviation	Min.	Max.	Percentiles 25th	50th (Median)	75th
Stylus 1	31	3.9677	.75206	2.00	5.00	4.0000	4.0000	4.0000
Stylus 2	31	4.0323	.65746	3.00	5.00	4.0000	4.0000	4.0000
Original stylus	31	3.7419	1.12451	1.00	5.00	3.0000	4.0000	5.0000

Friedman Test

Table 6.17: Ranks

Stylus name	Mean Rank
Stylus 1	2.02
Stylus 2	2.00
Original stylus	1.98

Table 6.18: Test Statistics[a]

N	31
Chi-Square	.023
df	2
Asymp. Sig.	.989

a. Friedman Test

A Friedman's test was conducted to determine whether participants had a differential rank ordered preference for the three styluses based on their comfort, ease to grip and press the button. The result of the analysis provided in **Table 6.18** shows that, there is no significant difference among the three products (stylus 1, stylus 2 and original stylus) $\chi^2(2, N=31) = .023$, $p>0.05$. In addition, the final Friedman test, the descriptive statistics and mean ranks for comparing overall easiness and comfortability of the stylus respectively depicted in **Table 6.16** and **Table 6.17.**

From Friedman test $\chi^2(2) = .023$, $p=.989$, it can be concluded that all the three styluses may be considered as an easy and comfortable to grip. And in this situation it is not important to conduct pairwise Wilcoxon tests to understand the favorable rankings difference among the three types of styluses.

6.2. Findings

After conducting nos. of exhaustive experiments in three phases, initially evaluating the usability of the haptic feedback system and tactile feeling on users and followed by

TH-1503_126105008

prototyped modified styluses. This was also again followed by experiment conducted to examine the usability of these two modified styluses and then finally experiment was conducted to compare the usability of the three stylus (the two modified stylus and the original one). From this experiments it was found that the system usability was good in general and furthermore the newly modified stylus 2 (with palm pressing) was found better than the original stylus for lifting and to perceive the virtual object's weight.

6.3. Conclusions

From the research work, it was found that, integration of virtual reality with haptic devices (that allow interacting with virtual model and sensing the object with more realism and interactivity) to evaluate the usability of consumer products is one perfect solution. And this was proved through experimentation, data collection and data analysis. Therefore, proper use of PHANToM Omni™ or similar haptic devices may help in reducing the overall cost of product design and development by avoiding repeated physical prototyping. In addition to this, participants were confident as the system implementation may increase the productivity and efficiency of the designers'. The stylus designed during this research with the palm pressing option also can be used for lifting virtual object and getting better weight perception; this may reduce dissatisfaction and pain during prolonged usage of the original stylus.

6.4. Recommendations

Based on the finding from experimental result, it is better to modify the stylus of the PHANToM Omni™ haptic device or other system with a kind of wired glove that allow to grip, manipulate the virtual object with maximum reachability and affordable price. This experiment has been done with a single PHANToM Omni^{TM} device but it is advisable and also should be possible to evaluate heavier object with both hand and to perform assembly of components virtually, if one more device is synchronous with the other device. Finally, there are possibilities of conducting research with the objective of reducing the price of haptic feedback system for affordability to facilitate its introduction in every design center and academic institute.

TH-1503_126105008

6.5. Key contribution

In this research work, it has been attempted to show with practical example that may create awareness towards the implementation of VR-haptic integration for usability evaluation of virtual products during the design and development phases and in design education for realization and understanding the abstract theory in VR which is not easy to understand. Usability study has been made on the stylus and it was found that participants experienced pain in their wrist during weight lifting and perception phenomena and resulted in dissatisfaction. To enhance usability of haptic device by nullifying the pain experienced by subjects, new design imitated and these were prototyped, tested for usability and compared with exiting stylus.

TH-1503_126105008

APPENDICES

Appendix A

Post-task System Usability questionnaire

Instructions:

Please read each statement and indicate how strongly agree or disagree with the statement by putting tick mark on the circle provided that describes your experience with the CAD-Haptic touch interface device integration. Use the PHANToM Omni™ haptic interface device to evaluate the characteristics.

1. Surface smoothness/roughness/irregularity,
2. Hardness/rigidity/stiffness,
3. Weight,
4. Form/Shape and,
5. Depth of the virtual object

Please specify your academic background **(Please select one of the following options)**						
B. Des	B. Tech	M. Des	M. Tech	PhD	Other:	
Name of the participant (Please enter your full name in 'CAPITAL' letter)						
Gender : Male Female						
Age Group						
	20-25	26-30	31-35	36-40	above 40	
What type(s) of Three Dimensional CAD modeling software have you been used? (Please select from listed or if it is not listed please write on the space provided for)						
Catia	Solid Works	SketchUp	ProE	SolidEdge	AutoCAD	Other:
What limitations have you encountered when using CAD for your prototyping?						
Have you ever used haptic feedback devices in a Virtual Environment to interact with Virtual object?						
Yes				No		

Questionnaires	strongly disagree	disagree	neutral	agree	strongly agree
I am able to feel the surface roughness of the virtual object	1	2	3	4	5
The system gives weight perception of virtual object	1	2	3	4	5
I am able to feel the stiffness of the Virtual object	1	2	3	4	5
I am able to feel the shape of virtual object	1	2	3	4	5
I feel comfortable using this system	1	2	3	4	5
It is helpful in modifying the design quickly before going for physical prototyping	1	2	3	4	5
I believe I could become productive and efficient Using this system	1	2	3	4	5
It was easy to learn to use this system	1	2	3	4	5
The system is effective in helping designers to complete their 3D form/Shape design task	1	2	3	4	5
It was simple to use this system	1	2	3	4	5
I am willing to use this system in future	1	2	3	4	5
I would recommend to colleague to use this system	1	2	3	4	5
This system may increase the Confidence of designer (s)	1	2	3	4	5
Cost of system is 13000USD equivalent to 792,155 Indian Rs, Do you agree it is affordable to small organization/institute	1	2	3	4	5
With the point contact, is it good enough to evaluate Virtual Object	1	2	3	4	5

Please describe briefly your feeling regarding this system?

………………………………………………………………………

TH-1503_126105008

Appendix B

Post-task Tactile perception questionnaire					
I can sense the Stiffness of carpet(s) using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Carpet one	Very less stiff	somewhat stiff	Stiff	More Stiff	Extremely Stiff
Carpet two	Very less stiff	somewhat stiff	Stiff	More Stiff	Extremely Stiff
I can sense the roughness of the carpet(s) using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Carpet One	Very smooth	Smooth	Unclear	Rough	Very rough
Carpet Two	Very smooth	Smooth	Unclear	Rough	Very rough
I can sense the rigidity of carpet(s) using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Carpet One	Very less Rigid	Somewhat rigid	Rigid	More Rigid	Extremely Rigid
Carpet Two	Very less Rigid	Somewhat rigid	Rigid	More Rigid	Extremely Rigid
I can sense the Irregularity/Coarseness of surface of carpet(s) using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Carpet One	Very less irregular	somewhat irregular	Irregular	More irregular	Extremely irregular
Carpet Two	Very less irregular	somewhat irregular	Irregular	More irregular	Extremely irregular
I can sense the hardness/softness of bottle(s) using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Bottle with Blue color cap	Very less stiff	somewhat stiff	stiff	More stiff	Extremely stiff

TH-1503_126105008

Bottle with Green color cap					
I can perceive the depth of the following Virtual object using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Pen-holder One	Very less depth	Less depth	Neutral	deeper	More Deeper
Pen-holder Two	Very less depth	Less depth	Neutral	deeper	More Deeper
I can feel the 3D form/Shape of the following virtual object (different plastic bottles) * (Please select one of the following options for each product/ object)					
Green color Water jar	Unclear	Very less clear	partially clear	Clear	Very clear
Green color oil Bottle	Unclear	Very less clear	partially clear	Clear	Very clear
I can feel the weight difference between the two battery operated Tea leaf plucking using the PHANToM Omni™ * (Please select one of the following options for each product/ object)					
Tea leaf plucking One	Weightless	Less weight	Neutral	Heavyweight	More heavyweight
Tea leaf plucking Two	Weightless	Less weight	Neutral	Heavyweight	More heavyweight

TH-1503_126105008

Appendix C

The interaction of Virtual object with haptic feedback device Evaluation instruction

Instruction

Thank you for your willingness to participate in this evaluation of the haptic force feedback with the Virtual environment. You will participate in interaction with a virtual object through haptic device (PHANToM Omni™ device). Thereafter, you will be asked to fill out a questionnaire about your experience. The interaction may take you 10 to15 minutes and we will be recorded the session for review and to be used in scholarly publications. All information that you provide us will be kept confidential. The recording of the session will be only reviewed and kept by the researcher. This activity is intended to evaluate usability of virtual objects and the haptic force feedback device with in the Virtual environment. We have solicited your help because we need an independent view of how the system helps designer/Engineer in evaluating virtual objects before proceeding to physical prototyping. You are requested to perform as per the instruction given and fill out the questionnaires.

Steps to be followed

1. Read the questionnaires carefully and feel free to ask the researcher when there is vaguely worded.
2. Go through the prepared virtual models files and drag and drop the files into the X3D viewer or the researcher would prepare this to you.
3. Use the system stylus to ***perceive/feel the weight, stiffness/rigidity/hardness, 3D form/shape, and surface smoothness and roughness*** of the virtual object (two carpets, two water bottles, oil bottles and water jar, and two tea leaf plucking model).
4. Fill out the questionnaires.
5. If you are not able to manage the device, please feel free to ask the researcher.

Consent

I have read the procedure described above and I grant the researchers permission to use the image/video and interview of my participation in the evaluation of the haptic force feedback with the Virtual environment. The videos are to be used in scholarly publications. I understand that I am not obligated to complete this part of the consent form and it will in no way impact my participation in the study. I understand that my name and personal information will be kept with strict confidentiality.

Full name ....………................

Signature and Date ....….........................

The researcher appreciates your candid and direct feedback.

TH-1503_126105008

Appendix D

Modified stylus usability testing questionnaires

Instructions:

Please read each statement and indicate how strongly agree or disagree with the statement by putting tick mark on the circle provided that describes your experience with the new modified stylus fitted on the original stylus given by the manufacturer to evaluate the surface texture of the bottle and weight of the Tea leaf plucking model (virtual objects).

3. its easiness and comfort during rubbing on the surface and perceiving the surface texture of the bottle and
4. Light weightiness easiness and painlessness during griping and lifting the Tea leaf plucking machine model.

Please specify your academic background (Please select one of the following options)

	B. Des.	M. Des.	B. Tech.	M.Tech.	Ph.D.	PostDoc.
Gender						
	Male		Female			
Age (in years): ……						

S.NO.	**statement**	**Codes**				
		1 strongly disagree	**2 disagree**	**3 neutral**	**4 agree**	**5 strongly agree**
1	I am able to feel the surface roughness of the virtual object					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
2	I am able to feel the weight of the virtual object					

TH-1503_126105008

	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
3	I felt comfortable using this stylus					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
4	it was easy to grip					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
5	it was comfortable and easy					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
6	it is light weight and comfortable to perceive the texture of the virtual object					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
7	it is light weight and comfortable to perceive the weight of the virtual					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5

TH-1503_126105008

8	it doesn't give any pain					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5
9	overall I am satisfied with how easy it to use this stylus					
	Stylus 1(stylus with thumb pressing)	1	2	3	4	5
	Stylus 2 (stylus with palm pressing)	1	2	3	4	5

TH-1503_126105008

Appendix E

Sample x3d (water bottle deformation haptic)

```
<X3D profile='H3DAPI' version='2.0'>
<head>
   <meta name='title' content='Green color cup_waterbottle.x3d'/>
   <meta name='description' content='Dynamic interaction between the haptics device and water jar.'/>
   <meta name='editors' content='hailu2014'/>
 </head>
<Scene DEF='scene'>
<Background skyColor='0.4 0.4 0.4'/>
    <GlobalSettings>

 <HapticsOptions useBoundTree='false' maxDistance='0.03'  lookAheadFactor='0.01' />
         <DebugOptions drawHapticTriangles='false' />
    </GlobalSettings>
<FitToBoxTransform boxCenter="0 0.02 -0.06" boxSize="0.5 0.5 0.5" uniformScalingOnly="true" active="true">
<Collision enabled="false">
   <Transform rotation=" 1 0 0 -1.2" >
     <Transform>
          <Group DEF='ALL'>
           <Group DEF='_338B92D8'>
             <DeformableShape>
                   <CoordinateDeformer plasticity='0'>
                   <GaussianFunction width="15"  mainButton='true' amplitude = '5' proxyWeighting = '0'  containerField="distanceToDepth"/>
         </CoordinateDeformer>
```


TH-1503_126105008

```
<Appearance>
<Material DEF='_material0' diffuseColor='0.1 0.1 0.9' ambientIntensity='0.2'
shininess='0.8'  emissiveColor='0 0.5 1' specularColor='0 1 0' transparency='0.4'/>
<SmoothSurface stiffness="0.5" />
</Appearance>
<IndexedFaceSet DEF='IND1'   solid='false' coordIndex='746 219 208 -1 219
218 208 -1 208 218 207 -1 218 217 207 -1 207 217 206 -1 '>
<Coordinate point='-6.542 -13.5384 60.4992 -6.58901 -13.6356 59.7326 '/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND1' containerField="hapticGeometry"/>
</DeformableShape>
<DeformableShape>
<CoordinateDeformer plasticity='0'>
<GaussianFunction   width="15"    mainButton='true'   amplitude   =   '5'
proxyWeighting = '0'  containerField="distanceToDepth"/>
</CoordinateDeformer>
<Appearance>
<Material USE='_material0'/>
<FrictionalSurface dynamicFriction="0.5" staticFriction="0.9"  stiffness="1.0"
/>
</Appearance>
<IndexedFaceSet DEF='IND2'      solid='false' coordIndex='735 83 72 -1 83
82 72 -1 72 82 71 -1 82 81 71 -1 '>
<Coordinate  point='6.58901  13.6356  59.7326  6.66691   -14.5476  3.65607
61.2725'/>
<Normal   vector='0.427524   0.884741   0.185625   -0.969841   0.243738
1.01064e-15'/>
</IndexedFaceSet>

<IndexedFaceSet USE='IND2' containerField="hapticGeometry"/>
</DeformableShape>
```


TH-1503_126105008

```
<DeformableShape>
    <CoordinateDeformer plasticity='0'>
    <GaussianFunction width="3"  mainButton='true' amplitude = '1' proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
  <Appearance>
   <Material USE='_material1'/>
 <FrictionalSurface dynamicFriction="0.3" staticFriction="0.6"  stiffness="1.0" />
   </Appearance>
  <IndexedFaceSet DEF='IND50'  solid='false' coordIndex='66 22 65 -1 22 23 65 -1 65 23 64 -1 23 24 64 -1 64 24 63 -1 24 25 63 -1 '>
   <Coordinate point='-8.36444 -13.0096 59.3776 -9.27122 -12.3797  -7.41504 -13.5731 59.3776'/>
   <Normal vector='0.54081 0.841145 0 0.599439 0.800421 0 0.54081 0.841145 0 0.479426 0.877583 0 0.479426 0.877583 0'/>
  </IndexedFaceSet>
 <IndexedFaceSet USE='IND50' containerField="hapticGeometry"/>
  </DeformableShape>
<DeformableShape>
    <CoordinateDeformer plasticity='0'>
    <GaussianFunction width="3"  mainButton='true' amplitude = '1' proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
  <Appearance>
   <Material USE='_material1'/>
  <FrictionalSurface dynamicFriction="0.3" staticFriction="0.6"  stiffness="1.0" />
   </Appearance>
```


TH-1503_126105008

```
<IndexedFaceSet DEF='IND51' solid='false' coordIndex='46 16 45 -1 16 17 45 -1 45 17 44 -1 17 18 44 -1 44 18 43 -1 18 19 43 -1'>
<Coordinate point='-3.27912 -6.00239 74.9752 -3.88857 -5.62674 74.9752 -4.45543 -5.18945 74.9752 -4.97347 -4.6953 74.9752 '/>
<Normal vector='0.479426 0.877583 0 0.568532 0.822661 0 0.651409 0.758727 0 0.727149 0.68648 0 '/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND51' containerField="hapticGeometry"/>
</DeformableShape>
<DeformableShape>
<CoordinateDeformer plasticity='0'>
<GaussianFunction width="3" mainButton='true' amplitude = '1' proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
<Appearance>
<Material USE='_material1'/>
<FrictionalSurface dynamicFriction="0.3" staticFriction="0.6" stiffness="1.0" />
</Appearance>
<IndexedFaceSet DEF='IND59' solid='false' coordIndex='0 93 1 -1 93 92 1 -1 1 92 2 -1 92 91 2 -1 2 91 3 -1 '>
<Coordinate point='-7.89446 -14.4507 74.9752 -6.88991 -14.9558 74.9752 '/>
<Normal vector='-0.479426 -0.877583 0 -0.41842 -0.908254 0 -0.355463 '/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND59' containerField="hapticGeometry"/>
</DeformableShape>
</Group>
<Group DEF='_27677978'>
<DeformableShape>
```


TH-1503_126105008

```
<CoordinateDeformer plasticity='0'>

<GaussianFunction width="3" mainButton='true' amplitude = '1'
proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
<Appearance>
<Material DEF='_material2' diffuseColor='0 1 0'/>

<FrictionalSurface dynamicFriction="0.3" staticFriction="0.6" stiffness="1.0"
/>
</Appearance>
<IndexedFaceSet DEF='IND60' solid='false' coordIndex='22 58 21 -1 58
59 21 -1 21 59 20 -1 59 60 20 -1 20 60 19 -1 '>
<Coordinate point='-3.89964 -8.9664 87.8815 -3.0802 -9.27987 87.8815 '/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND60' containerField="hapticGeometry"/>
</DeformableShape>
<DeformableShape>
<CoordinateDeformer plasticity='0'>
<GaussianFunction width="3" mainButton='true' amplitude = '1'
proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
<Appearance>
<Material USE='_material2'/>
<FrictionalSurface dynamicFriction="0.3" staticFriction="0.6" stiffness="1.0"
/>
</Appearance>
<IndexedFaceSet DEF='IND61' solid='false' coordIndex='81 80 0 -1 80 79
0 -1 0 79 1 -1 79 78 1 -1 1 78 2 -1 '>
```


TH-1503_126105008

```
<Coordinate point='5.22727 11.6596 84.8815 4.29636 12.0337 84.8815 '/>
<Normal vector='0.409093 0.912493 0 0.336239 0.941777 0 0.261311 0.877583 0'/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND61' containerField="hapticGeometry"/>
</DeformableShape>
<DeformableShape>
<CoordinateDeformer plasticity='0'>
<GaussianFunction width="3" mainButton='true' amplitude = '1' proxyWeighting = '0' containerField="distanceToDepth"/>
</CoordinateDeformer>
<Appearance>
<Material USE='_material2'/>
<FrictionalSurface dynamicFriction="0.3" staticFriction="0.6" stiffness="1.0" />
</Appearance>
<IndexedFaceSet DEF='IND80' solid='false' coordIndex='0 61 1 -1 61 60 1 -1 1 60 2 -1 60 59 2 -1 2 59 3 -1 59 58 3 -1 3 58 4 -1 58 57 4 -1 4 57 5 -1 57 56 5 -1 5 56 6 -1 '>
<Coordinate point='-3.37613 -6.17997 86.5756 -2.71165 -6.49902 86.5756 '/>
<Normal vector='-0.479426 -0.877583 0 -0.385067 -0.922889 0 '/>
</IndexedFaceSet>
<IndexedFaceSet USE='IND80' containerField="hapticGeometry"/>
</DeformableShape>
</Group>
</Group>
</Transform>
</Transform>
</Collision>
```


TH-1503_126105008

```
  </FitToBoxTransfo
<PythonScript DEF='PS'  url='DeformableShape.py' >
   <Group USE='ALL' containerField="references" />
 </PythonScript>
 </Scene>
</X3D>
```


TH-1503_126105008

Appendix F

Sample x3d (water bottle shape haptic)

```
<?xml version="1.0" encoding="utf-8"?>
<X3D profile='H3DAPI' version='1.4'>
  <head>
    <meta name='title' content='bottle_shape.x3d'/>
    <meta name='author' content='Hailu_IITG'/>
  </head>
  <Scene>
<Background skyColor='0.6 0.4 0.4'/>
    <GlobalSettings>
            <HapticsOptions useBoundTree='false'  maxDistance='0.04'
  lookAheadFactor='0.01' />
      <DebugOptions drawHapticTriangles='false' />
    </GlobalSettings>
<FitToBoxTransform boxCenter="0.0 0.04 0.0" boxSize="0.275 0.275 0.275"
uniformScalingOnly="true" active="true">
<Transform rotation="0.15 0.15 0.2 -1.75" >

  <Collision enabled="false">
         <Group DEF='AAA'>
             <Shape>
               <Appearance DEF='A'>
                    <FrictionalSurface dynamicFriction="0.2" staticFriction="0.3"
stiffness="1.0"  damping="1.0"/>
                      <Material diffuseColor='0.38 0.67 0.63' ambientIntensity='0.3'/>
                </Appearance>
                  <IndexedFaceSet solid='false' coordIndex='15 9 14 -1 9 10 14 -1 14 10 13 -1
10 11 13 -1 13 11 12 -1 6 18 5 -1 18 19 5 -1 5 19 4 -1 19 20 4 -1 4 20 3 -1 20 21 3 -1 3 21
```


TH-1503_126105008

2 -1 21 22 2 -1 2 22 1 -1 22 23 1 -1 1 23 0 -1 15 8 9 -1 8 15 16 -1 16 7 8 -1 7 16 17 -1 17 6 7 -1 6 17 18 -1'>

<Coordinate point='-4.62394 165.749 147.291 -4.61489 165.395 147.153 -4.58709 165.023 147.058 -4.53984 164.637 147.013 -4.49254 164.349 147.011 -4.4344 164.06 147.037 -4.34168 163.686 147.114 -4.23105 163.324 147.238 -4.10372 162.981 147.407 -3.96157 162.663 147.618 -3.80539 162.372 147.87 -3.62472 162.097 148.182 3.62472 162.097 148.182 3.77521 162.322 147.921 3.91598 162.573 147.69 4.04608 162.845 147.49 4.18292 163.187 147.3 4.30283 163.55 147.155 4.40437 163.93 147.059 4.47048 164.233 147.018 4.5246 164.537 147.009 4.58045 164.958 147.047 4.61327 165.364 147.143 4.62395 165.749 147.291'/>

<Normal vector='0 -0.424145 0.905594 0 -0.306346 0.95192 0 -0.182152 0.98327 0 -0.0535549 0.998565 0 0.0423735 0.999102 0 0.138704 0.990334 0 0.263581 0.964637 0 0.384133 0.923278 0 0.498373 0.866963 0 0.604412 0.796672 0 0.701383 0.712784 0 0.793285 0.60885 0 0.793285 0.60885 0 0.718139 0.695899 0 0.634614 0.772829 0 0.543724 0.839264 0 0.429883 0.902884 0 0.308755 0.951142 0 0.182286 0.983245 0 0.0810943 0.996706 0 -0.0202541 0.999795 0 -0.160547 0.987028 0 -0.296021 0.955181 0 -0.424145 0.905594'/>

</IndexedFaceSet>

</Shape>

……………………

……………………

……………………

<Shape>

<Appearance USE='A'/>

<IndexedFaceSet solid='false' coordIndex='0 1 2 -1 0 2 3 -1 0 3 4 -1 0 4 5 -1 0 5 6 -1 0 6 7 -1 0 7 8 -1 0 8 9 -1 0 9 10 -1 0 10 11 -1 0 11 12 -1 0 12 13 -1 0 13 14 -1 0 14 15 -1 0 15 16 -1 0 16 17 -1 0 17 18 -1 0 18 19 -1 0 19 20 -1 0 20 21 -1 0 21 22 -1 0 22 23 -1 0 23 24 -1 0 24 25 -1 0 25 26 -1 0 26 27 -1 0 27 28 -1 0 28 29 -1 0 29 30 -1 0 30 31 -1 0 31 32 -1 0 32 33 -1 0 33 34 -1 0 34 35 -1 0 35 36 -1 0 36 37 -1 0 37 38 -1 0 38 39 -1 0

TH-1503_126105008

```
39 40 -1 0 40 41 -1 0 41 42 -1 0 42 43 -1 0 43 44 -1 0 44 45 -1 0 45 46 -1 0 46 47 -1 0 47
48 -1 0 48 49 -1 0 49 50 -1 0 50 51 -1'>
            <Coordinate point='-50 20 6.34035 -50 20 216.34 -50 88.453 216.34 -50
117.905 165.327 -50 120.755 162.929 -50 123.555 160.472 -50 126.304 157.958 -50
128.999 155.387 -50 131.641 152.762 -50 134.229 150.082 -50 136.76 147.349 -50
139.234 144.564 -50 141.649 141.729 -50 144.006 138.844 -50 146.303 135.911 -50
148.538 132.932 -50 150.711 129.906 -50 152.821 126.837 -50 154.867 123.724 -50
156.848 120.57 -50 158.764 117.375 -50 160.613 114.141 -50 162.395 110.87 -50
164.108 107.563 -50 165.753 104.221 -50 167.329 100.845 -50 168.834 97.438 -50
170.268 94.0002 -50 171.631 90.5336 -50 172.922 87.0395 -50 174.14 83.5194 -50
175.285 79.9749 -50 176.357 76.4074 -50 177.354 72.8185 -50 178.278 69.2097 -50
179.126 65.5826 -50 179.899 61.9388 -50 180.596 58.2797 -50 181.218 54.607 -50
181.763 50.9222 -50 182.232 47.2269 -50 182.624 43.5227 -50 182.94 39.8112 -50
183.179 36.0939 -50 183.341 32.3725 -50 183.426 28.6485 -50 183.433 24.9236 -50
183.364 21.1993 -50 183.218 17.4772 -50 182.994 13.759 -50 182.694 10.0462 -50
182.317 6.34035'/>
           </IndexedFaceSet>
          </Shape>
      </Group>
</Collision>
</Transform>
</FitToBoxTransform>
<PythonScript DEF='PS'  url='Form_Shape.py' >
   <Group USE="AAA" containerField="references" />
  </PythonScript>
</Scene>
</X3D>
```

Indian Institute of Technology Guwahati

TH-1503_126105008

Appendix G

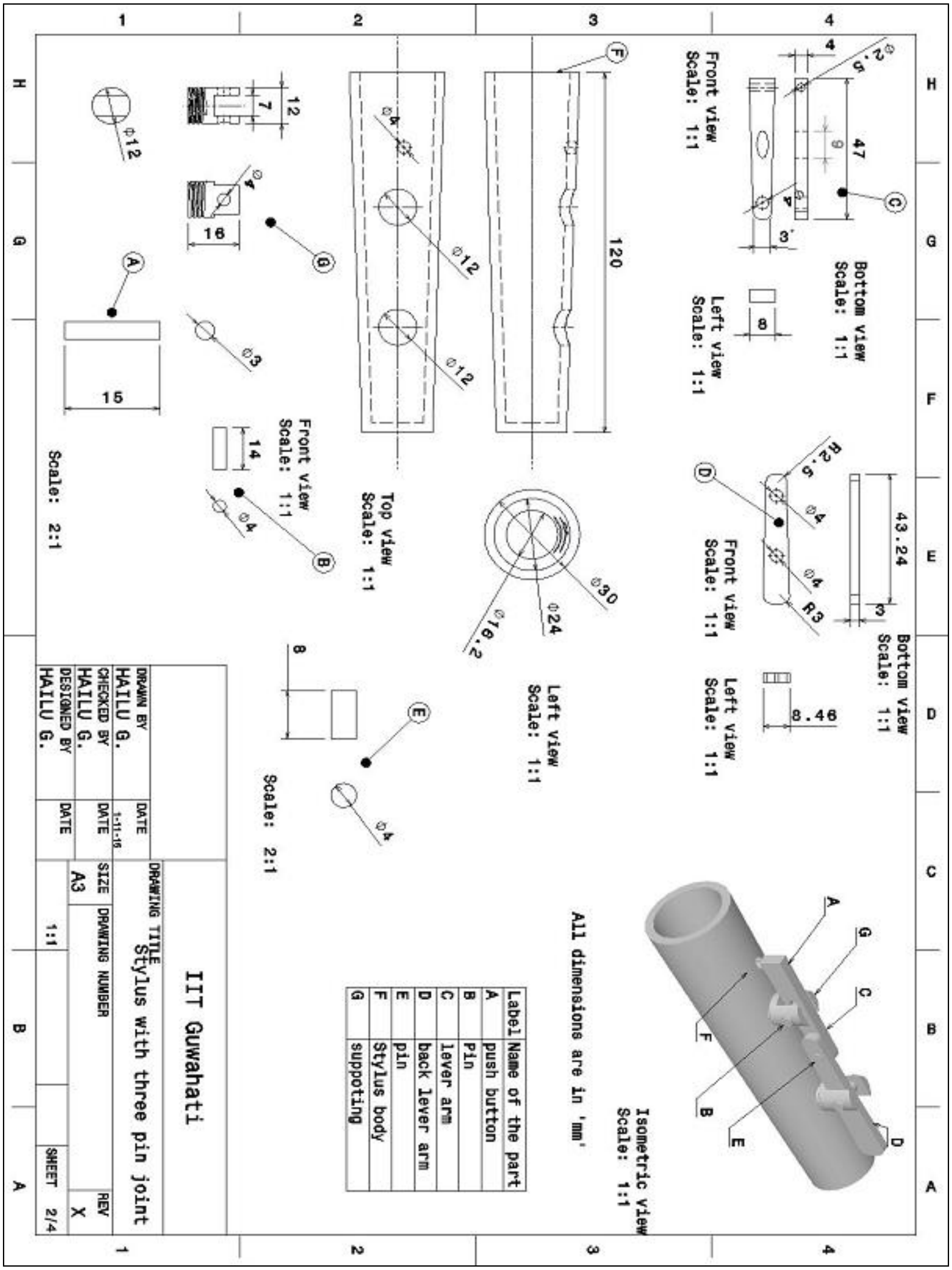


Figure App_G.1: Stylus model with three joint

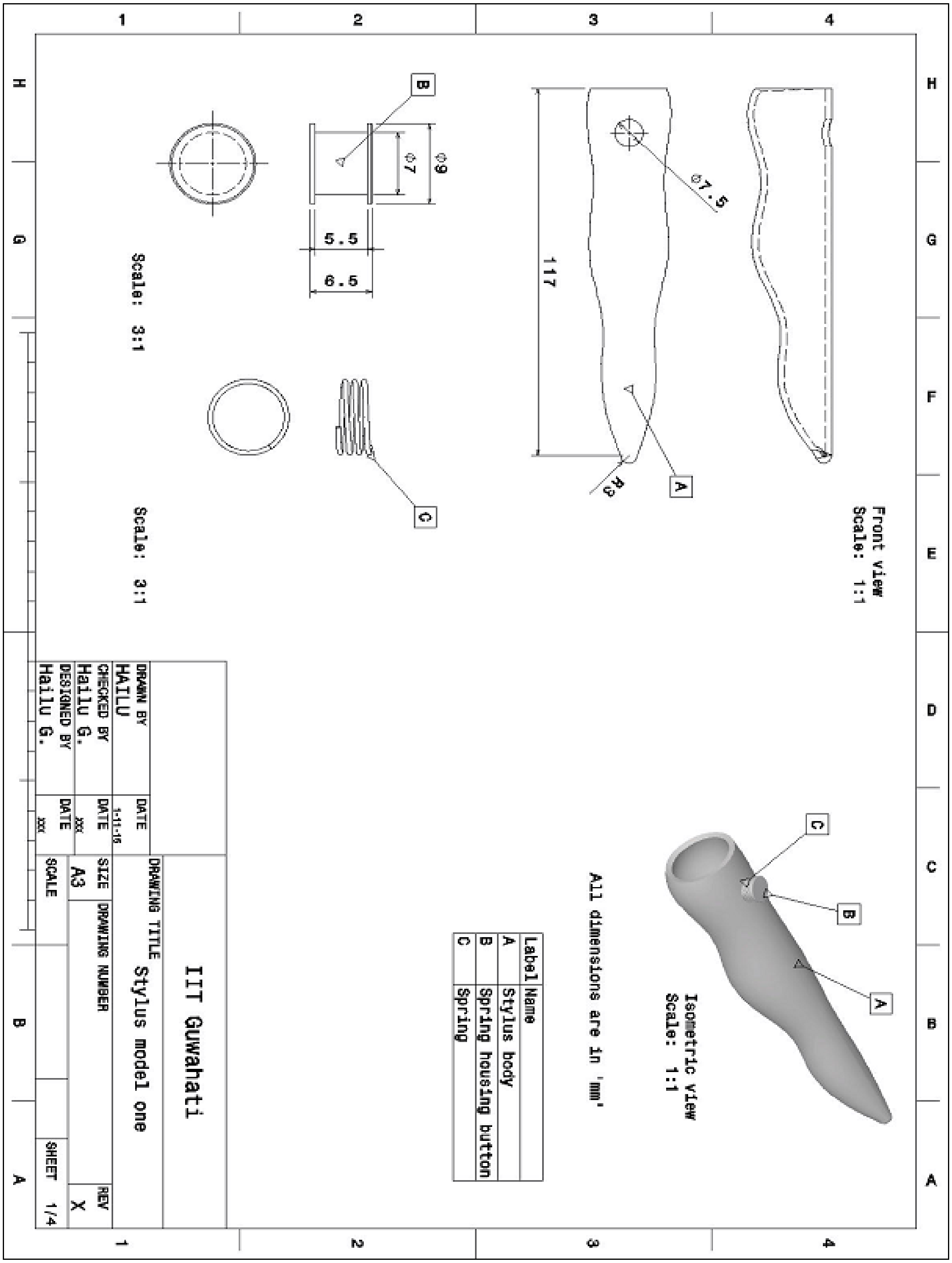


Figure App_G.2: Stylus model with thumb button and gripping shape

TH-1503_126105008

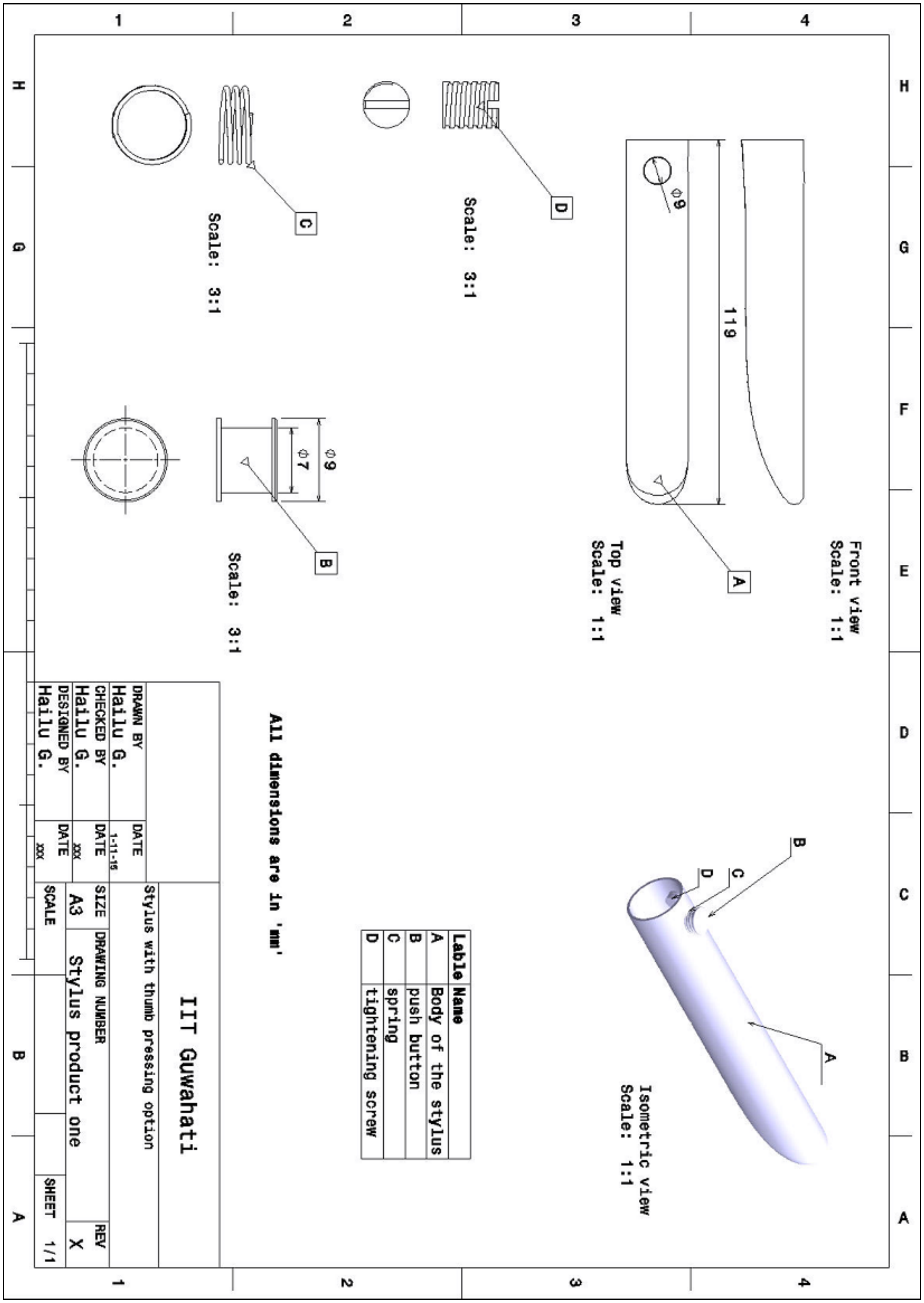


Figure App_G.3: Stylus model with thumb pressing option

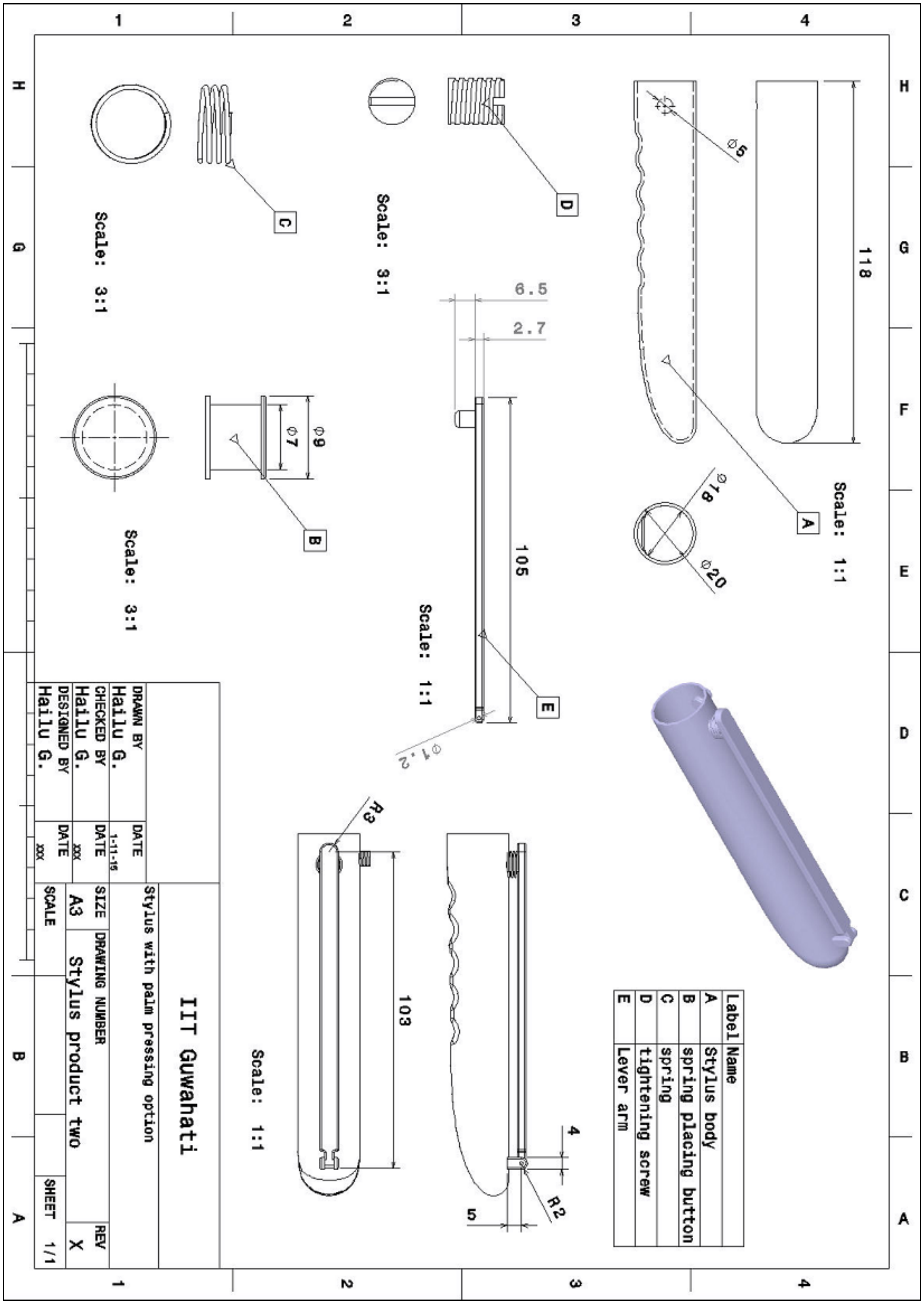


Figure App_G.4: Stylus model with palm pressing option

Appendix F

PUBLICATIONS OUT OF THE CURRENT RESEARCH:

Hailu Gebretsadik Teklemariam, Vikramjit Kakati, Amarendra Kumar Das, (2014), Application of VR Technology in Design Education, Proceedings of the E&PDE 2014 16th International conference on Engineering and Product Design, University of Twente, The Netherlands, pp (117-122).

Hailu Gebretsadik & A. K. Das, (2014), The intervention of Virtual reality and Tactile Feedback Technology in Consumer product design, *International Ergonomics Conference HWWE 2014*

Hailu Gebretsadik and A. K. Das. (2015). A case study of Phantom Omni force feedback device for virtual product design. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-12.

Hailu Gebretsadik and A. K. Das. (2015). Integrated Virtual/Augmented Reality and haptics feedback technology for Defence and industrial applications. National conference - Defence University, (NCETCPDIC-2015), Ethiopia.

Hailu Gebretsadik and A. K. Das. Design modification of phantom Omni stylus to make it more accessible to users. International Journal of product development (IJPD-140690: under review).

TH-1503_126105008

REFERENCES

3D Systems Corporation. (2013). Phantom Omni Device Guide-Geomagic.

Abulrub, A.-H. G., Attridge, A. N., Williams, M., & others. (2011). Virtual reality in engineering education: The future of creative learning. In *Global Engineering Education Conference (EDUCON), 2011 IEEE* (pp. 751–757). IEEE.

Anderson, P., Ma, M., & Poyade, M. (2014). A haptic-based virtual reality head and neck model for dental education. In *Virtual, Augmented Reality and Serious Games for Healthcare 1* (pp. 29–50). Springer.

Ang, Q.-Z., Horan, B., Najdovski, Z., & Nahavandi, S. (2011). Grasping virtual objects with multi-point haptics. In *Virtual reality Conference (VR), 2011 IEEE* (pp. 189–190). IEEE.

Arbeláez-Estrada, J. C., & Osorio-Gómez, G. (2013). Augmented Reality Application for Product Concepts Evaluation. *Procedia Computer Science*, *25*, 389–398.

Arroyave, S., Osorio-Gómez, G., & Hoyos, J. (2014). Assessment of ergonomic issues during product conceptualization stage in augmented reality environments. Innovation on product design and manufacture, Medellin, Colombia.

Augmented Reality introduction. (2007). *BMW augmented reality*. Retrieved October 10, 2014. from http://www.bmw.com/com/en/owners/service/augmented_reality_introduction_1.html

Aziz, E.-S. S., Chang, Y., Esche, S. K., & Chassapis, C. (2015). Virtual Mechanical Assembly Training Based on a 3D Game Engine. *Computer-Aided Design and Applications*, *12*(2), 119–134.

Basdogan, C., & Ho, C. (2002). Principles of haptic rendering for virtual environments. *Network. Ku. Edu. Tr/~cbasdogan/Tutorials/haptic_tutorial. html*.

TH-1503_126105008

Basdogan, C., Laycock, S. D., Day, A. M., Patoglu, V., & Gillespie, R. B. (2007). 3-DOF haptic rendering. *Haptic Rendering*.

Billinghurst, M. (2002). Augmented reality in education. *New Horizons for Learning*, *12*. Retrieved from http://www.solomonalexis.com/downloads/ar_edu.

Bordegoni, M., Colombo, G., & Formentini, L. (2006). Haptic technologies for the conceptual and validation phases of product design. *Computers & Graphics*, *30*(3), 377–390.

Cassidian - Virtual Military Training Systems. (2012). Retrieved April 15, 2015, from http://www.army-technology.com/contractors/training/cassidian-cp/cassidian-cp3.html

Chen, C. J., Ong, S. K., Nee, A. Y. C., & Zhou, Y. Q. (2010). Haptic-based interactive path planning for a virtual robot arm. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *4*(2), 113–123.

Chen, R.-J., Lin, H.-W., Chang, Y.-H., Wu, C.-T., & Lee, S.-T. (2011). Development of an augmented reality force feedback virtual surgery training platform. *International Journal of Automation and Smart Technology*, *1*(1), 41–51.

Chen, Y., Yang, Z., & Lian, L. (2005). On the development of a haptic system for rapid product development. *Computer-Aided Design*, *37*(5), 559–569.

Christophe Grujon. (2008). All About Robotic Surgery. Retrieved April 5, 2015, from http://allaboutroboticsurgery.com/forcehapticfeedback.html

Dworkin, P., & Zeltzer, D. (1993). *A New Model for Efficient Dynamic Simulation. Proceedings fourth Eurographics workshop on Animation and simulation*,

El Saddik, A., Orozco, M., Eid, M., & Cha, J. (2011). Haptics: general principles. In *Haptics Technologies* (pp. 1–20). Springer.

Etheredge, C. E., Kunst, E. E., & Sanders, A. J. B. (2013). Harnessing the GPU for Real-Time Haptic Tissue Simulation. *Journal of Computer Graphics Techniques (JCGT)*, *2*(2), 28–54.

TH-1503_126105008

Falcão, C. S., & Soares, M. M. (2013). Application of virtual reality technologies in consumer product usability. In *Design, User Experience, and Usability. Web, Mobile, and Product Design* (pp. 342–351). Springer.

Fällman, D., Backman, A., & Holmlund, K. (1999). VR in education: An introduction to multisensory constructivist learning environments. In *Conference on University Pedagogy (Umea University, Umea, Sweden, February 18-19)*.

Field, A. (2009). *Discovering statistics using SPSS*. Sage publications.

Furht, B. (2011). *Handbook of augmented reality*. Springer Science & Business Media.

Gao, Z., Wang, J., & Jiang, Z. (2012). Haptic perception evaluation for the virtual prototyping of elastic hand-held product designs: A method to simulate how hand-held products are felt during their daily usage is presented and the use of haptic technology is highlighted. *Virtual and Physical Prototyping*, *7*(2), 117–128.

Gosselin, F., Bouchigny, S., Mégard, C., Taha, F., Delcampe, P., & d'Hauthuille, C. (2013). Haptic systems for training sensorimotor skills: a use case in surgery. *Robotics and Autonomous Systems*, *61*(4), 380–389.

Granados, A. (2008). Haptic Deformable Shapes Using Open Source Libraries. *Published September*.

H3D.org. (2008). Beginner X3D and H3DAPI. Retrieved January 5, 2014, from http://www.h3dapi.org/modules/mediawiki/index.php/Beginner_X3D_and_H3DAPI

Hailu Gebretsadik, A. K. D. (2014). The intervention of Virtual reality and Tactile feedback Technology in Consumer product design. In *International Ergonomics conference*. INDIA: McGraw-Hill Education (India) Private Limited.

Haptic Feedback Technology. (2012). Retrieved March 10, 2015, from http://www.haptic-feedback.com/2012/04/sense-of-touch-in-haptic-feedback.html

Heller, M. A., & Schiff, W. (2013). *The psychology of touch*. Psychology Press. Tayler & Frances group.

TH-1503_126105008

Howard, B. M., & Vance, J. M. (2007). Desktop haptic virtual assembly using physically based modelling. *Virtual reality*, *11*(4), 207–215.

Iman Brouwer. (2012). Haptic Interfaces. Retrieved February 20, 2015, from http://www.bracina.com/haptichardware.html.

Immonen, L. (2008). Haptics in military applications. *Diss. University of Tampere (December 2008)*.

inglobe. (2011). Augmented Reality and the Future of Printing and Publishing – Whitepaper. Retrieved October 10, 2014, from http://arblog.inglobetechnologies.com/?p=446

Jayaram, S., Connacher, H. I., & Lyons, K. W. (1997). Virtual assembly using virtual reality techniques. *Computer-Aided Design*, *29*(8), 575–584.

Kadlecek, P. (2011). Overview of current developments in haptic APIs. *Proceedings of CESCG*.

Kesim, M., & Ozarslan, Y. (2012). Augmented reality in education: current technologies and the potential for education. *Procedia-Social and Behavioral Sciences*, *47*, 297–302.

Lantada, A. D., & Morgado, P. L. (2012). Rapid prototyping for biomedical engineering: current capabilities and challenges. *Annual Review of Biomedical Engineering*, *14*, 73–96.

Laycock, S. D., & Day, A. M. (2007). A survey of haptic rendering techniques. In *Computer Graphics Forum* (Vol. 26, pp. 50–65). Wiley Online Library.

Lele, A. (2013). Virtual reality and its military utility. *Journal of Ambient Intelligence and Humanized Computing*, *4*(1), 17–26.

Li, J.-R., Khoo, L. P., & Tor, S. B. (2003). Desktop virtual reality for maintenance training: an object oriented prototype system (V-REALISM). *Computers in Industry*, *52*(2), 109–125.

TH-1503_126105008

Lindeman, R. W., Page, R., Yanagida, Y., & Sibert, J. L. (2004). Towards full-body haptic feedback: the design and deployment of a spatialized vibrotactile feedback system. In *Proceedings of the ACM symposium on Virtual reality software and technology* (pp. 146–149). ACM.

Liu, Y., & Laycock, S. D. (2010). Creating Continuous Force Feedback for Haptic Interaction of Volume Data Sets.

Michalski, R. (2014). The influence of color grouping on users' visual search behavior and preferences. *Displays*, *35*(4), 176–195.

Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). *Computers & Education*, *56*(3), 769–780.

Nee, A. Y. C., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals-Manufacturing Technology*, *61*(2), 657–679.

Novint Falcon. (2007). Retrieved February 20, 2015, from http://cs.stanford.edu/people/conti/falcon.html

Novint Technologies Incorporated. (2008). Haptic Device Abstraction Layer (HDAL) Programmer's Guide.

Omega Haptic Device. (2005). Retrieved February 20, 2015, from http://cs.stanford.edu/people/conti/omega.html

Onyesolu, M. O., Ezeani, I., & Okonkwo, O. R. (2012). *A Survey of Some Virtual reality Tools and Resources*. INTECH Open Access Publisher.

Onyesolu, M. O., & Eze, F. U. (2011). *Understanding Virtual reality Technology: Advances and Applications*. INTECH Open Access Publisher.

Pantelidis, V. S. (2010). Reasons to use virtual reality in education and training courses and a model to determine when to use virtual reality. *Themes in Science and Technology Education*, *2*(1-2), pp–59.

TH-1503_126105008

Parsons, T. D., & Trost, Z. (2014). Virtual reality graded exposure therapy as treatment for pain-related fear and disability in chronic pain. In *Virtual, Augmented Reality and Serious Games for Healthcare 1* (pp. 523–546). Springer.

Peltola, S. M., Melchels, F. P., Grijpma, D. W., & Kellomäki, M. (2008). A review of rapid prototyping techniques for tissue engineering purposes. *Annals of medicine*, *40*(4), 268-280.

Pontonnier, C., Dumont, G., Samani, A., Madeleine, P., & Badawi, M. (2014). Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions. *Journal on Multimodal User Interfaces*, *8*(2), 199–208.

Pungotra, H. (2012). Virtual reality in Concept Design. *International Journal on Manufacturing and Material Science*, *2*(1), 35.

Ran, Y., & Wang, Z. (2011). Virtual and augmented reality applications in industrial design. *3rd international conference on machine learning and computing* (ICMLC 2011).

Robles-De-La-Torre, G. (2006). The importance of the sense of touch in virtual and real environments. *Ieee Multimedia*, (3), 24–30.

Robles-De-La-Torre, G. (2008). Principles of haptic perception in virtual environments. In *Human haptic perception: Basics and applications* (pp. 363–379). Springer.

Ruspini, D. C., Kolarov, K., & Khatib, O. (1997). The haptic display of complex graphical environments. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (pp. 345–352). ACM Press/Addison-Wesley Publishing Co.

Sabater, J. M., García, N., Pérez, C., & Azorín, J. M. (2008). Algorithm for haptic rendering of reconstructed 3D solid organs. *International Journal of Computer Assisted Radiology and Surgery*, *3*(5), 387–393.

Salisbury, J. K., Srinivasan, M., & others. (1997). Phantom-based haptic interaction with virtual objects. *Computer Graphics and Applications, IEEE*, *17*(5), 6–10.

TH-1503_126105008

Salisbury, K., Conti, F., & Barbagli, F. (2004). Haptic rendering: introductory concepts. *Computer Graphics and Applications, IEEE*, *24*(2), 24–32.

SenseGraphics, A. B. (2014, June 13). H3D API Manual for Version 1.3.

Seth, A., Su, H.-J., & Vance, J. M. (2005). A desktop networked haptic VR interface for mechanical assembly. In *ASME 2005 international mechanical engineering congress and exposition* (pp. 173–180). American Society of Mechanical Engineers.

Sherrice Gilsbach, (2014), how Ford Uses Virtual reality in Product Development, Retrieved October 10, 2014, from http://www.at.ford.com/

Sherman, W. R., & Craig, A. B. (2002). *Understanding virtual reality: Interface, application, and design*. Elsevier.

Srinivasan, M. A. (1995). What is haptics? *Laboratory for Human and Machine Haptics: The Touch Lab, Massachusetts Institute of Technology*.

Srinivasan, M. A., & Basdogan, C. (1997). Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, *21*(4), 393–404.

Tangram Technology Ltd. (1998). *Design and materials cost reduction*. Retrieved from http://www.tangram.co.uk/GI-Costs-3.html

Teklemariam, H. G., & Das, A. K. (2015). A case study of phantom omni force feedback device for virtual product design. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1–12.

Teklemariam, H. G., Kakati, V., & Das, A. K. (2014). Application of VR Technology in Design Education. In *DS 78: Proceedings of the E&PDE 2014 16th International conference on Engineering and Product Design, University of Twente, The Netherlands*.

Touchscreen Landscapes. (2014). Retrieved April 15, 2015, from http://bldgblog.blogspot.in/2014/10/touchscreen-landscapes.html

TH-1503_126105008

Ullman, D. (2010). *The mechanical design process* (4th edition). McGraw-Hill Science/Engineering/Math.

Ulrich, K. T. (2003). *Product design and development*. Tata McGraw-Hill Education.

VR and Medical Training: (2014). Retrieved April 15, 2015, from http://virtualrealitymichelleokeeffe.tumblr.com/post/101434643913/vr-and-medical-training

Winn, W. (1993). A conceptual basis for educational applications of virtual reality. *Technical Publication R-93-9, Human Interface Technology Laboratory of the Washington Technology Center, Seattle: University of Washington*.

Xia, P., Lopes, A. M., Restivo, M. T., & Yao, Y. (2012). A new type haptics-based virtual environment system for assembly training of complex products. *The International Journal of Advanced Manufacturing Technology*, *58*(1-4), 379–396.

Yadav, S., & Krishnaiah, R. V. (2013). Haptic science and technology. *international Journal of Computer Engineering and Applications, 2(1)*:139-146.

Ye, J., Badiyani, S., Raja, V., & Schlegel, T. (2007). Applications of virtual reality in product design evaluation. In *Human-computer interaction. HCI applications and services* (pp. 1190–1199). Springer.

Zilles, C. B. (1995). *Haptic rendering with the toolhandle haptic interface*. Citeseer.

Zilles, C. B., & Salisbury, J. K. (1995). A constraint-based god-object method for haptic display. In *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on* (Vol. 3, pp. 146–151). IEEE.

TH-1503_126105008